MWPS-22

Low Temperature & Solar Grain Drying

Handbook

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LOW TEMPERATURE & SOLAR GRAIN DRYING HANDBOOK

This handbook is organized into two major subjects that are largely independent: low temperature grain drying and principles of solar heating.

Low temperature grain drying has been used in the North Central region for decades. (USDA Leaflet 332, 1952: Drying Shelled Corn and Small Grain with Unheated Air.) Recent work is improving understanding of sound management practices and reducing dependence on fossil fuels and in many cases electrical energy.

The book gives the principles of low temperature grain drying and recommends practices for the North Central region. When and how supplemental heat can be useful is presented, with emphasis on applying heat from solar energy.

The principles of collecting, storing, and using solar energy are presented as completely as technology and experience allow at this time. These basics apply to many farm uses for heat, including grain drying, for which specific recommendations are given.

Plans for several types of collectors are included. The plans are examples—there are many effective adaptations and alternatives.

Although solar energy is free, the facilities needed to use it are not. The economic benefits of a solar system are difficult to assess. First, costs vary with how the heat is used, how much equipment is homemade, possible government incentives, etc. Second, benefits are measured against the value of fuels replaced. As this is being written, fuel costs are changing so rapidly that any projection is highly suspect.

Development of this book was supported by Agricultural Research, Science and Education Administration of the United States Department of Agriculture, with funds provided by the Department of Energy. As with all Midwest Plan Service projects, a regional committee of engineers provided the information and directed the development.

The authors are agricultural engineers in both extension and research who have experience with grain drying and/or solar energy. Their knowledge, collected throughout the North Central region over many years, has been combined into the best recommendations that could be identified. As with any new technology, refinement of ideas and recommendations is ongoing.

You may wish to browse the whole book before studying sections of specific interest. Much recent technology is included, and some systems and management programs may be new to you. An idea of what is on later pages may help you understand and interpret particular sections.

LOW TEMPERATURE DRYING

Low temperature drying, as used in this handbook, is a process of slow drying with natural air or air heated only a few degrees (2 F to 10 F). Grain is dried and stored in the same bin so the process is sometimes referred to as in-storage drying. It is also called deep-bed drying and is one method of in-bin drying.

The bin usually is equipped with a fully perforated floor. Provide a fan capable of supplying at least 1 cubic foot of air per minute per bushel (cfm/bu) and exhaust vents of 1 sq ft/1000 cfm of fan capacity. Equipping each bin with a grain distributor to spread fines is recommended, Fig 1. A stirring device is sometimes installed, but is not essential.

Drying depends on the air's ability to evaporate water so its relative humidity is a key factor. The lower the relative humidity of the drying air, the more water the air evaporates from the grain, resulting in a lower final grain moisture content. The air's ability to evaporate water is referred to as **drying potential.** It is influenced by temperature as well as relative humidity.

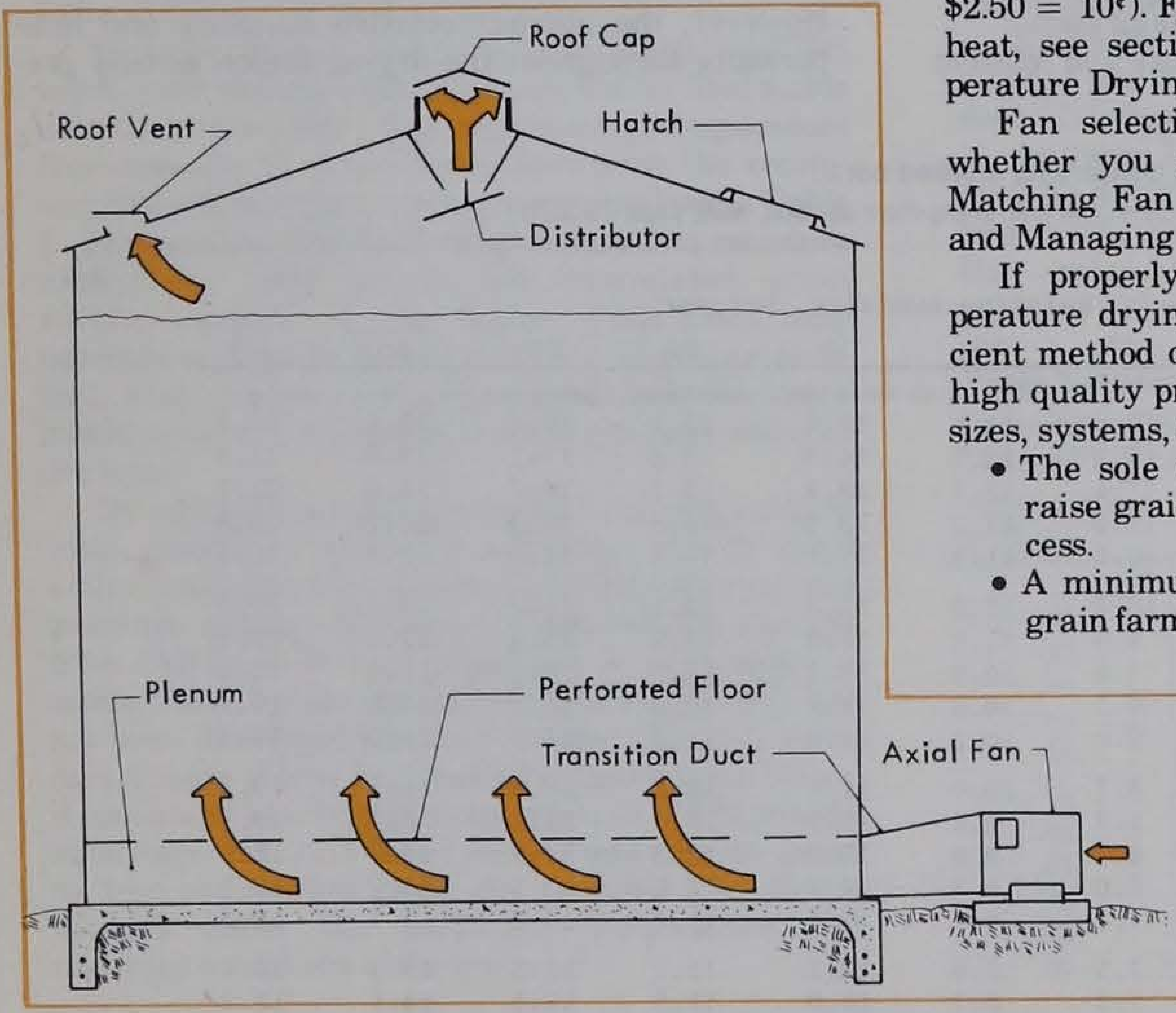

Fig 1. Typical drying bin.

A drying fan heats the air and reduces its relative humidity. As fan power increases, heat added to the air increases. Supplemental heat, sometimes from a solar collector, has often been added.

Whether you use supplemental heat or not depends on the drying potential of the air in your area and the final moisture content you want. Often, the natural air along with heat from the fan is sufficient for drying corn* in the North Central region. (For more information, see Equilibrium Moisture Content.) Corn dries to a moisture content for safe winter storage (18% or less) 9 years out of 10 during the fall drying season. Spring drying is needed some years to reach a safe long-term storage moisture content (13% to 14%).

Supplemental heat causes costly overdrying in low temperature dryers without stirring machines: **1**) You do not sell the maximum amount of water allowed for #2 yellow corn, and **2**) You pay for the energy to overdry.

Estimate the cost of overdrying at 2% of corn market price/point of drying below 15.5%/bushel. That is, corn dried to 13.5% and sold for $2.50/bu costs you 10¢ per bushel (2% x 2 points x $2.50 = 10¢). For more information on supplemental heat, see sections Airflow—the Key to Low Temperature Drying and Supplemental Heat.

Fan selection and management are the same whether you add supplemental heat or not. See Matching Fan to Bin for Low Temperature Drying and Managing a Low Temperature Dryer.

If properly designed and managed, low temperature drying can be an economical, energy efficient method of conditioning grain that results in a high quality product. It works with a variety of farm sizes, systems, and farm enterprises. It can be:

- The sole drying system for livestockmen who raise grain for feed and want to market the excess.
- A minimum investment system for small cash grain farms.

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*Most research has been directed to low temperature drying of corn so the text is specific for corn. Although principles for the low temperature drying of other crops are similar, recommendations are scarce. For available information see Table 24, appendix.

- One method of increasing the capacity of a high temperature dryer by using a combination high temperature/low temperature system.
- The major drying system for a large cash grain farm with a well designed multi-bin set-up.

Advantages of low temperature drying include:

- Minimum grain handling.
- Good quality grain (few stress cracks, high test weight).
- Less dependence on petroleum based fuels.
- High drying efficiency (few purchased Btu/lb of water removed) because it uses atmospheric heat.

Disadvantages of low temperature drying include:

- Initial moisture content limitations.
- High electrical power demand (connected kilowatts).
- Weather dependency.
- Possible limitation on fill rate.

Principles of Low Temperature Drying

Equilibrium Moisture Content

Low temperature grain drying works because grain readily gives up its moisture to the air. Corn dries in the field while still on the stalks—the principle is the same in a bin except air must be forced through the grain with a fan. When air is forced through grain, the air evaporates moisture from the grain.

For each temperature and relative humidity combination of the drying air there is a corresponding moisture content for the grain. If the air is kept at constant conditions, the grain eventually reaches a moisture content close to that indicated in Table 1—the grain is in equilibrium with the air. Table 1 gives **equilibrium moisture contents** for corn.

In grain drying, the air temperature and relative humidity are not constant. The average temperature /relative humidity combination throughout the drying period determines the final moisture content. Table 1, however, gives you an idea of the final grain moisture content that can be reached using only natural air.

Example 1. If the outside air averages 50 F and 70% relative humidity, to what moisture content will the air dry the corn? Answer: 15.4%.

Notice the effect of temperature. As air gets warmer, it dries grain to a lower moisture content for the same relative humidity. High humidity drying air dries wet grain (moisture content about 24%) as long as temperature is above freezing.

Supplemental heat increases the drying air temperature, and reduces relative humidity. Use Table 1 to estimate the final moisture content when heat is added. Reduce the relative humidity by 10 points for each 5 F of heat added.

Example 2. In example 1, the outside air was 50 F, 70% relative humidity. If 5 F is added, what will be the final corn moisture content?

Answer: The new temperature is 55 F and relative humidity is reduced to 60%: the corn will dry to 13.5% moisture content.

Table 1 is also useful in determining air conditions within the grain mass. Knowing these conditions allows you to evaluate the storability of the grain. The section, Mold Growth and Spoilage , gives more information.

Example 3. If corn is 20% moisture and 50 F, what is the relative humidity within the grain mass? Answer: about 90%.

Grain can rewet if the air passing through it is at a high relative humidity for an extended time. However, the average relative humidity and temperature throughout the drying season usually pre-

Table 1. Equilibrium moisture content for shelled corn.
Dashed lines indicate examples in text. (Developed from Chung-Pfost equation, ASAE paper 76-3520.)

Temp. deg. F	Relative humidity, percent 10	20	30	40	50	60	70	80	90
	Equilibrium moisture content, percent								
20	9.4	11.1	12.4	13.6	14.8	16.1	17.6	19.4	22.2
25	8.8	10.5	11.9	13.1	14.3	15.6	17.1	19.0	21.8
30	8.3	10.1	11.4	12.7	13.9	15.2	16.7	18.6	21.1
35	7.9	9.6	11.0	12.3	13.5	14.8	16.3	18.2	20.8
40	7.4	9.2	10.6	11.9	13.1	14.5	16.0	17.9	20.5
45	7.1	8.8	10.2	11.5	12.8	14.1	15.7	17.6	20.5
50	6.7	8.5	9.9	11.2	12.5	13.8	15.4	17.3	20.2
55	6.3	8.2	9.6	10.9	12.2	13.5	15.1	17.0	20.0
60	6.0	7.9	9.3	10.6	11.9	13.3	14.8	16.8	19.7
65	5.7	7.6	9.0	10.3	11.6	13.0	14.6	16.5	19.5
70	5.4	7.3	8.7	10.0	11.4	12.7	14.3	16.3	19.3
75	5.1	7.0	8.5	9.8	11.1	12.5	14.1	16.1	19.1
80	4.9	6.7	8.2	9.6	10.9	12.3	13.9	15.9	18.9
85	4.6	6.5	8.0	9.3	10.7	12.1	13.7	15.7	18.7
90	4.4	6.3	7.7	9.1	10.4	11.9	13.5	15.5	18.5
95	4.1	6.0	7.5	8.9	10.2	11.7	13.3	15.3	18.4
100	3.9	5.8	7.3	8.7	10.0	11.5	13.1	15.1	18.2

vents grain from rewetting above about 17%. You can expect corn to rewet to within about 1 percentage point below the equilibrium moisture contents given in Table 1. If air would dry wet grain to 18%, the same air would rewet dry grain to 16% or 17%.

Rewetting can be helpful in low temperature grain drying. For instance, air is drier in early fall and temperatures are warmer. This combination causes grain in the lower part of the bin to overdry.

As winter approaches, relative humidity increases and air temperature decreases. You would expect little drying under these conditions. However, as the air passes through the lower layers of the overdried grain, moisture is taken out of the air. Drying continues in the upper layers. Overdried grain also dehumidifies the air on rainy and foggy days and evens out the day-night differences in relative humidity to allow drying to continue during the night. Therefore, operate fans continuously during drying if there is wet corn (greater than 18% moisture content) in the top of the bin.

Mold Growth and Spoilage

Mold is the major cause of spoilage in grain. There are two groups of mold that affect grain quality: field molds and storage molds.

Field molds invade kernels while grain is still in the field. Generally, they grow in high moisture grain (greater than about 20%) at temperatures of 30 F to 90 F. The high moisture content and cool temperatures of grain in the top of a low temperature drying bin resemble field conditions so some spoilage in a low temperature dryer results from field molds. Fall temperatures of 40 F to 50 F reduce mold activity, and prevent major spoilage. Once the grain is dried, these molds die, or become inactive.

Storage molds dominate in storage facilities when grain moisture content is too low for field molds (less than about 20%). The moisture and temperature requirements of these molds determine the recommended safe storage moisture contents given in Table 2. Because the effects of temperature and moisture content on mold growth are interrelated, grain moisture content can be higher when grain temperature is kept below about 40 F with proper aeration, management, and close observation. For summer long-term storage, safe storage moisture contents are lower.

By controlling moisture content and temperature, mold growth is restricted and grain can be dried without significant spoilage. Grain temperature and moisture content determine the **allowable storage time (AST)**—how long grain can be kept before it spoils. Table 3 gives the AST of shelled corn. (AST has not been developed for other grains.) The AST gives an estimate of how long you have to dry grain before it spoils and how long you can maintain grain quality in storage. The AST is the time it takes for the grain to drop one market grade due to moldy kernels developed under the particular temperature and moisture conditions of the grain.

Table 2. Safe storage moisture for aerated good quality grain.

Grain	Maximum safe moisture content
Shelled corn and sorghum	
To be sold as #2 grain or equiv by spring	15½%
To be stored up to 1 year	14%
To be stored more than 1 year	13%
Soybeans	
To be sold by spring	14%
To be stored up to 1 year	12%
Wheat	13%
Small grain (oats, barley, etc)	13%
Sunflowers	9%

Notice that as grain moisture content increases for a given temperature, the AST for drying and storing decreases. Also, as temperature increases, AST decreases. The AST is approximately cut in half for each 10 F increase in temperature, and cut in half for each 2 percentage points increase in moisture content. Mechanical damage also affects AST. Clean grain and whole seeds are more resistant to mold.

The AST is used to design low temperature drying systems. The recommended airflow rate is chosen so that drying finishes within the AST. Some examples show how to use AST to estimate how long you have to dry grain.

Example 4. Grain is harvested at 24% moisture and grain temperature is 50 F. How much time do you have before the grain drops one market grade?

Answer: about 25 days, Table 3. If conditions in the bin remain constant, the grain will drop one market grade in about 25 days, the AST at 24% moisture content and 50 F.

Example 5. If at the end of 7 days, the corn in Example 4 has dried to 20% moisture and is at 40 F, how does AST change?

Answer: During the first 7 days, 7/25 of the AST from Ex 4 was used up; 18/25 remain. The AST for the new conditions, 20% and 40 F, is 142 days, Table 3. But, only 18/25 of that time remains: 142 x 18/25 = 102 days. The AST is extended by drying.

Table 3. Allowable storage time for shelled corn.
Dashed lines indicate examples in text. (Developed from Thompson, Transactions of ASAE 333-337, 1972.)

Grain temp. deg. F	Corn moisture, percent 18	20	22	24	26	28	30
			- - - days - - -				
30	648	321	190	127	94	74	61
35	432	214	126	85	62	49	40
40	288	$\boxed{142}$	84	56	41	32	27
45	192	95	56	37	27	21	18
50	128	63	37	$\boxed{25}$	18	14	12
55	85	42	25	16	12	9	8
60	56	28	17	11	8	7	5
65	42	21	13	8	6	5	4
70	31	16	9	6	5	4	3
75	23	12	7	5	4	3	2
80	17	9	5	4	3	2	2

How Drying Occurs in a Bin

In a low temperature drying system without stirring, grain is dried in zones as shown in Fig 2. Air flows up through the grain, evaporating and carrying away water. Drying takes place in a drying zone 1' to 2' thick. The drying zone advances through the grain at a rate largely determined by airflow and the drying potential of the air.

The characteristics of three zones can be identified. The first zone is the **dry grain.** It is about the temperature of the drying air. The moisture content is close to that given in Table 1.

In the **drying zone,** grain is drying and the moisture content is less than the moisture content when the bin was filled, but the grain has not yet reached moisture equilibrium with the air. The grain temperature is less than the drying air temperature because evaporation of water causes cooling.

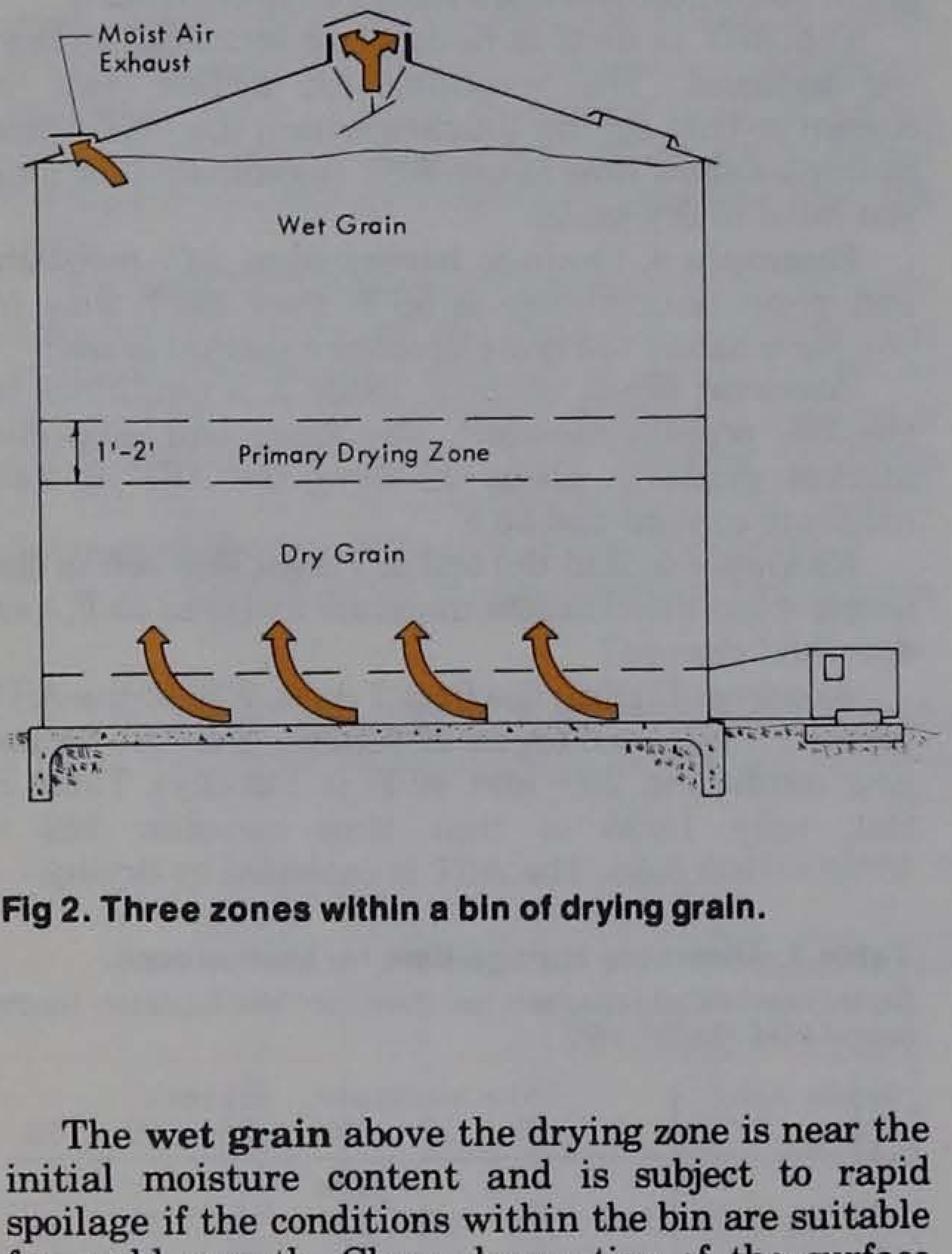


Fig 2. Three zones within a bin of drying grain.

The **wet grain** above the drying zone is near the initial moisture content and is subject to rapid spoilage if the conditions within the bin are suitable for mold growth. Close observation of the surface grain is critical to the success of low temperature grain drying. This grain must be dried within the allowable storage time (AST). If the surface grain begins to spoil, it must be removed and dried by some other method.

The AST is somewhat longer than expected because the air leaving the drying zone is cooler than the entering air which extends the AST of the wet grain.

In example 3, conditions within the bin were 90% relative humidity for 20% moisture content corn at 50 F. These conditions are favorable for mold growth. The temperature in the top layer, however, can be as low as 40 F—this 10 degree difference can extend AST by about 50%.

Airflow

Airflow—the Key to Low Temperature Drying

Airflow rate largely determines drying time. It is measured in cubic feet per minute (cfm); recommendations are in airflow per bushel (cfm/bu). The air's ability to evaporate water from the grain (drying potential) mostly affects final moisture content, but also affects drying time.

There are two ways to reduce drying time. Note that the two are not equal in effect.

- **Increase the airflow rate**—more air moving through the grain carries out more water. Drying speed is proportional to airflow. If airflow increases 25%, drying rate also increases by 25%.
- **Raise drying air temperature** to increase water-carrying capacity, Ex 2. During an extended period of damp, cold weather, added heat permits drying to continue. During more normal weather, added heat increases the speed of the drying front, but very little if corn moisture content is below about 24%. Supplemental heat also increases the amount and rate of water removal, but primarily from the lower part of the bin, resulting in overdrying. See section on Supplemental Heat.

Compare the progress of the drying front in the example bins in Fig 3. Each bin is the same: 30' diameter with 17.5' of shelled corn (about 9,900 bu). The bins differ only in the way they are equipped and their energy requirements. Initial corn moisture content is 22%. Drying begins Oct. 15.

Notice that bin #1, with 1.1 cfm/bu, finishes drying in 8 weeks. When 2.5 F of supplemental heat is added, Bin #2 finishes in 7 weeks and the final average moisture content is lower because of overdrying in the bottom.

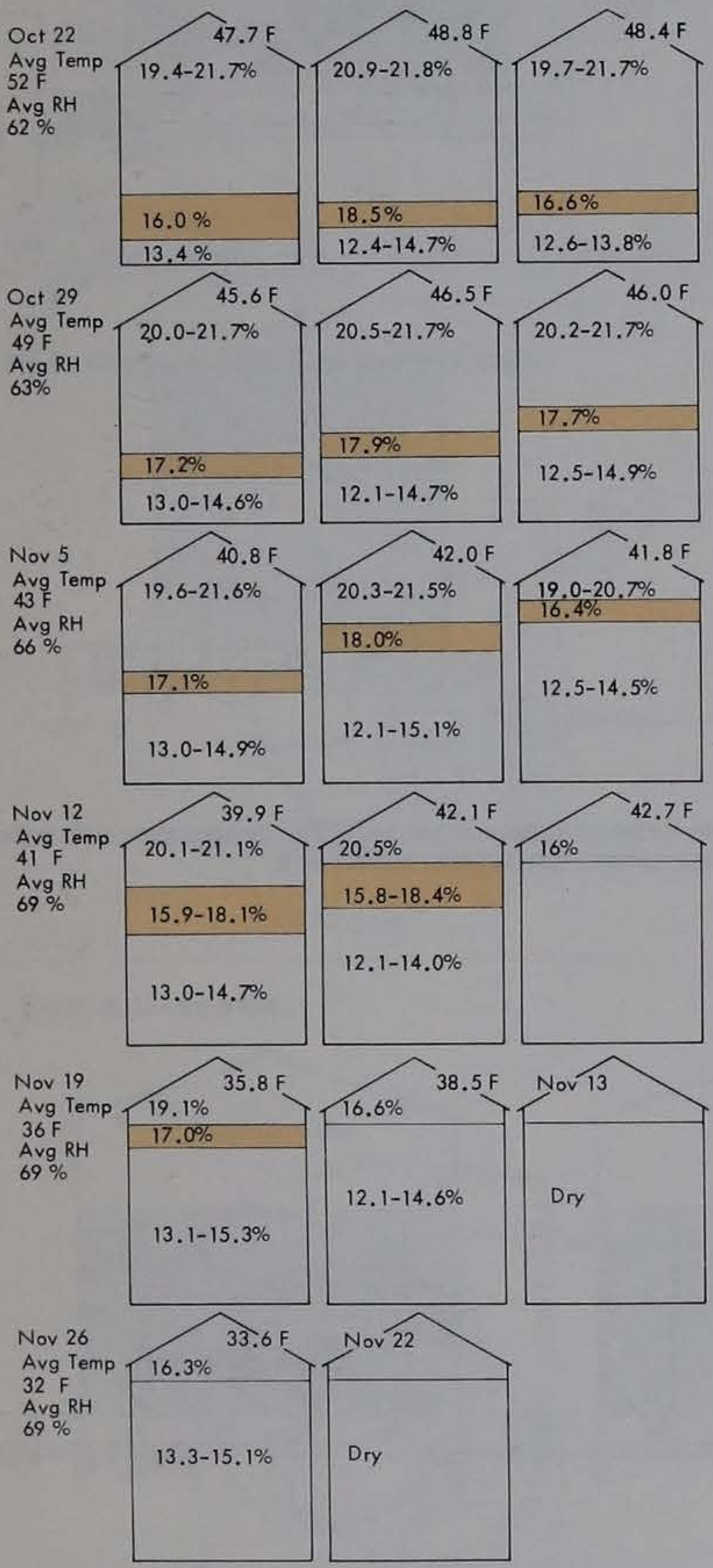
When airflow is increased to 1.4 cfm/bu, Bin #3 finishes in the fifth week. The final average moisture content is also lower than that of bin #1. The lower final moisture content is mainly because drying is completed earlier in the fall when the drying potential of the air is usually better.

The example bins show that airflow is the key to low temperature drying. The more air that is delivered, the faster the drying front moves through the grain, the greater the amount of water removed, and the more reliable the system is. Supplemental heat does not permit reducing airflow, nor does it make up for inadequate airflow. Because grain in the top does not dry much faster, added heat does not reduce the chance of spoilage. The section, "Supplemental Heat", gives more information.

Fig 3. Progress of drying front.

Based on 28 years of average weather data for Des Moines, IA. Temperature shown in top of bin is wet-grain temperature.

Bin #1	Bin #2	Bin #3
10 Hp	10 Hp	20 Hp
1.1 cfm/bu	1.1 cfm/bu	1.4 cfm/bu
3.13" SP	3.13" SP	4.63" SP
2.5° from fan	2.5° from fan	3.8° from fan
	2.5° supplemental heat (electric)	



Date dry	Nov. 30	Nov. 22	Nov. 13
MC range	13.3% to 15.5%	12.1% to 15.2%	12.5% to 15.4%
Avg. final MC	14.2%	13.2%	13.4%
Temp. range	34.5 F to 34 F	41 F to 39.2 F	44.8 F to 42.7 F
Fan hours, drying	1104	912	696
Kilowatt hrs. used	9,685	16,027	12,212

Airflow Resistance and Static Pressure

There are practical limits to how much airflow can be delivered to a full bin because the grain acts as a barrier. This **airflow resistance** is greatly influenced by airflow, grain depth, and type of grain. Grain cleanliness and the amount of packing are other factors, Fig 4. The fan must overcome this resistance.

Static pressure is the driving force a fan provides to push air through a mass of grain. It is measured in inches of water. Fig 5 shows how static pressure is measured in a bin. In the figure, static pressure below the grain is 2" of water. Atmospheric pressure is 0" of water. Air flows through the grain because the pressure below the grain is higher than atmospheric pressure above the grain.

Select a fan that can overcome the resistance in your particular bin system and deliver the required airflow. The section, Matching Fan to Bin for Low Temperature Drying , gives more information.

Fans

Types of Fans

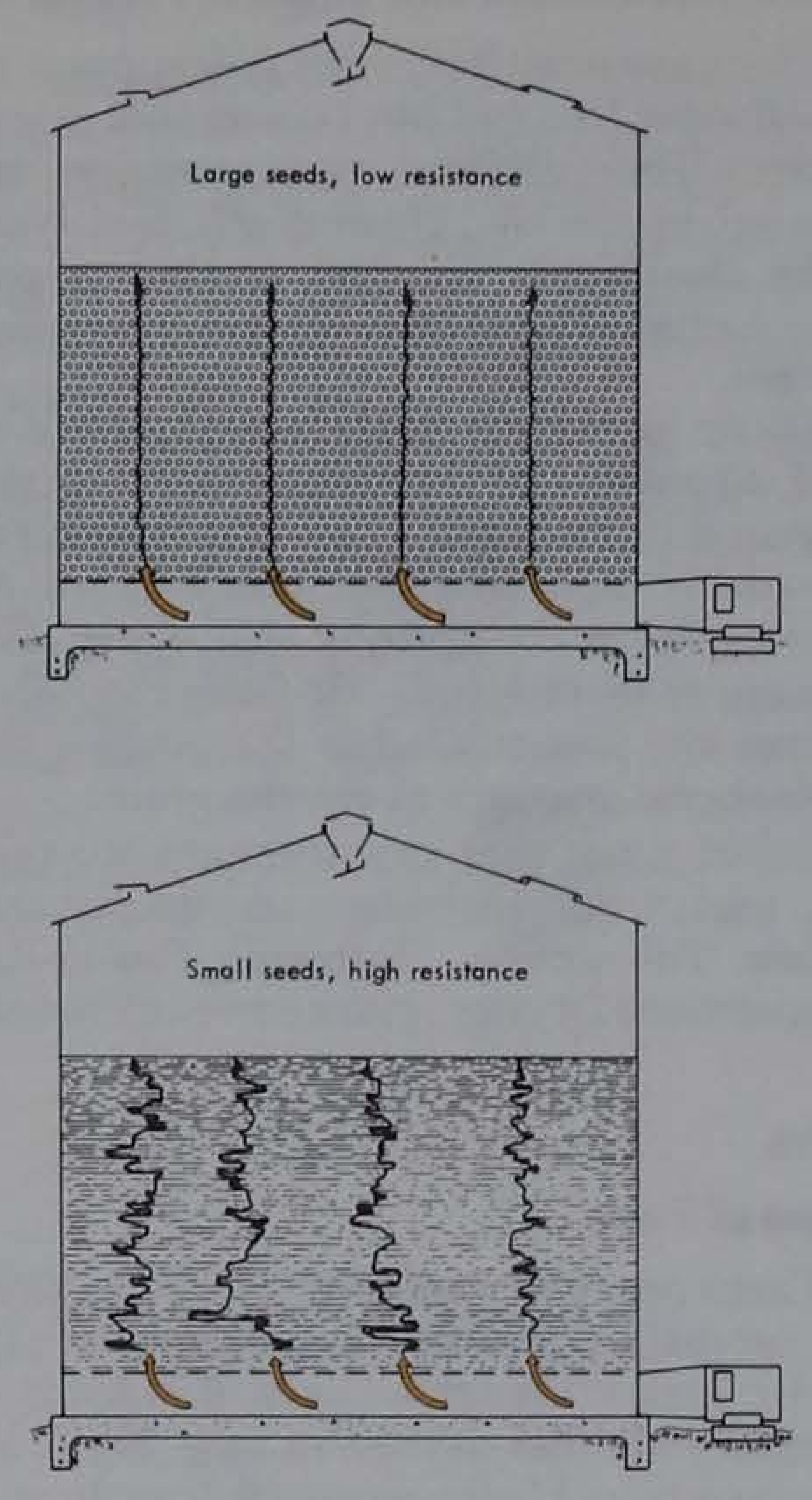
There are two types of fans for grain drying: axial-flow (propeller) and centrifugal (squirrel cage).

Air passes through an axial-flow fan in a direction generally parallel to the fan axis, Fig 6. Most axial-flow fans have blades mounted directly on the motor shaft. The fan is in a cylindrical housing.

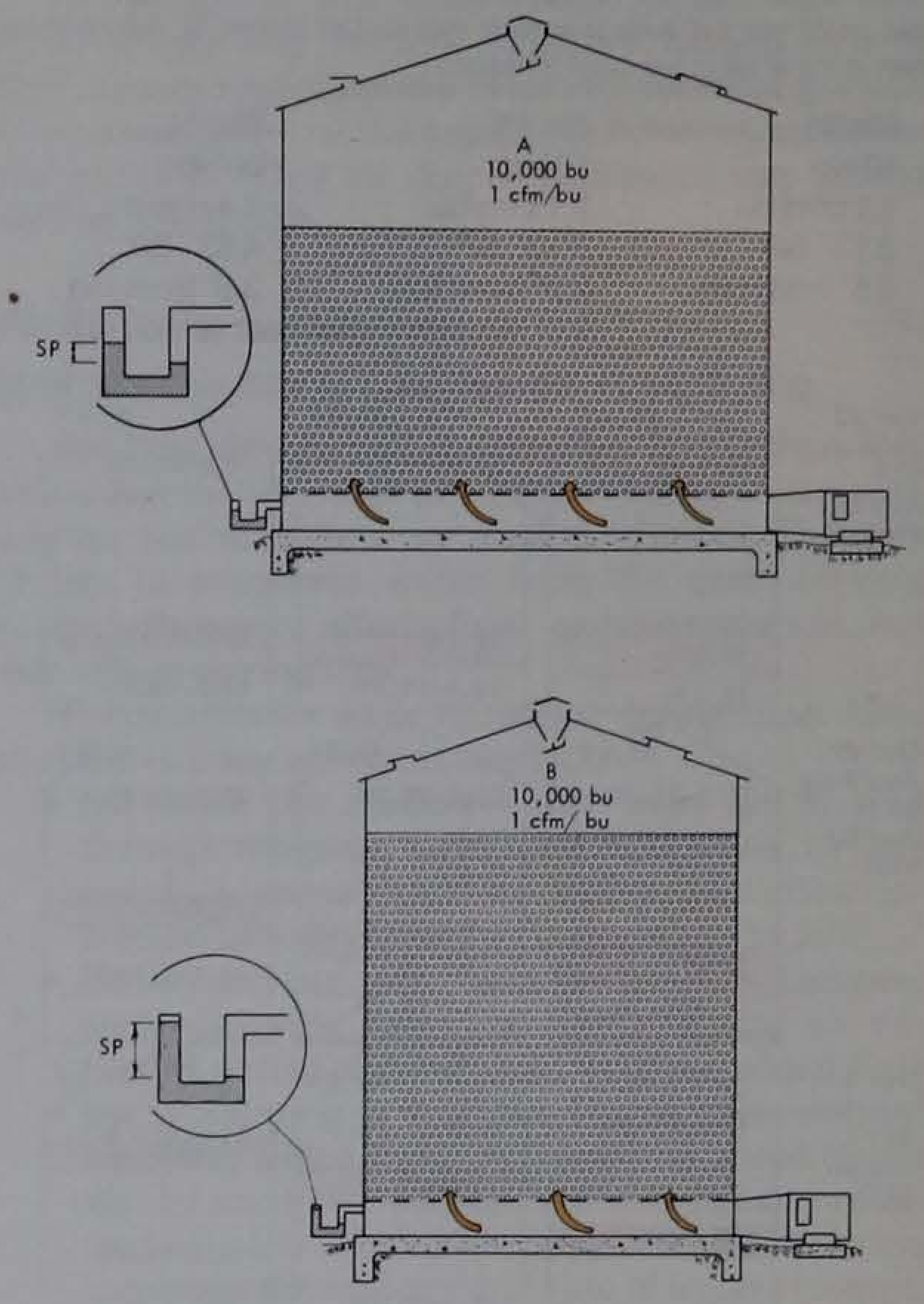
Most centrifugal fans used in grain drying are the backward-curved type—the rotor blades curve back away from the direction of rotation, Fig 7. Centrifugal fans are quieter, but may be more expensive to buy.

If an axial-flow and a centrifugal fan of the same horsepower rating are compared, the axial-flow fan usually delivers more air at less than 3.5" of static pressure. Generally, a centrifugal fan performs better when higher static pressure (greater than 4.5") is required. For static pressures between 3.5" and 4.5", consider both types. Axial-flow fans have an advantage in layer filling because the fan operates a significant portion of the time when the bin is less than full (low static pressure).

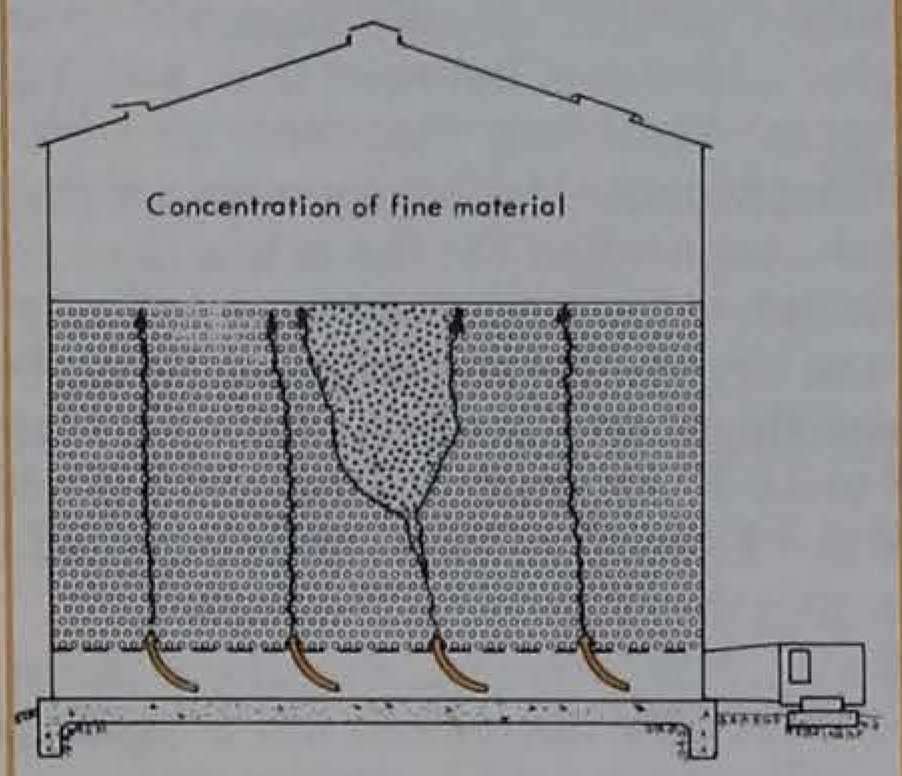
Fans heat the drying air and increase its drying potential. A centrifugal fan increases drying air temperature 1.5 F to 3.5 F. An axial-flow fan usually adds more heat (2 F to 4 F) because its motor is mounted in the airstream.



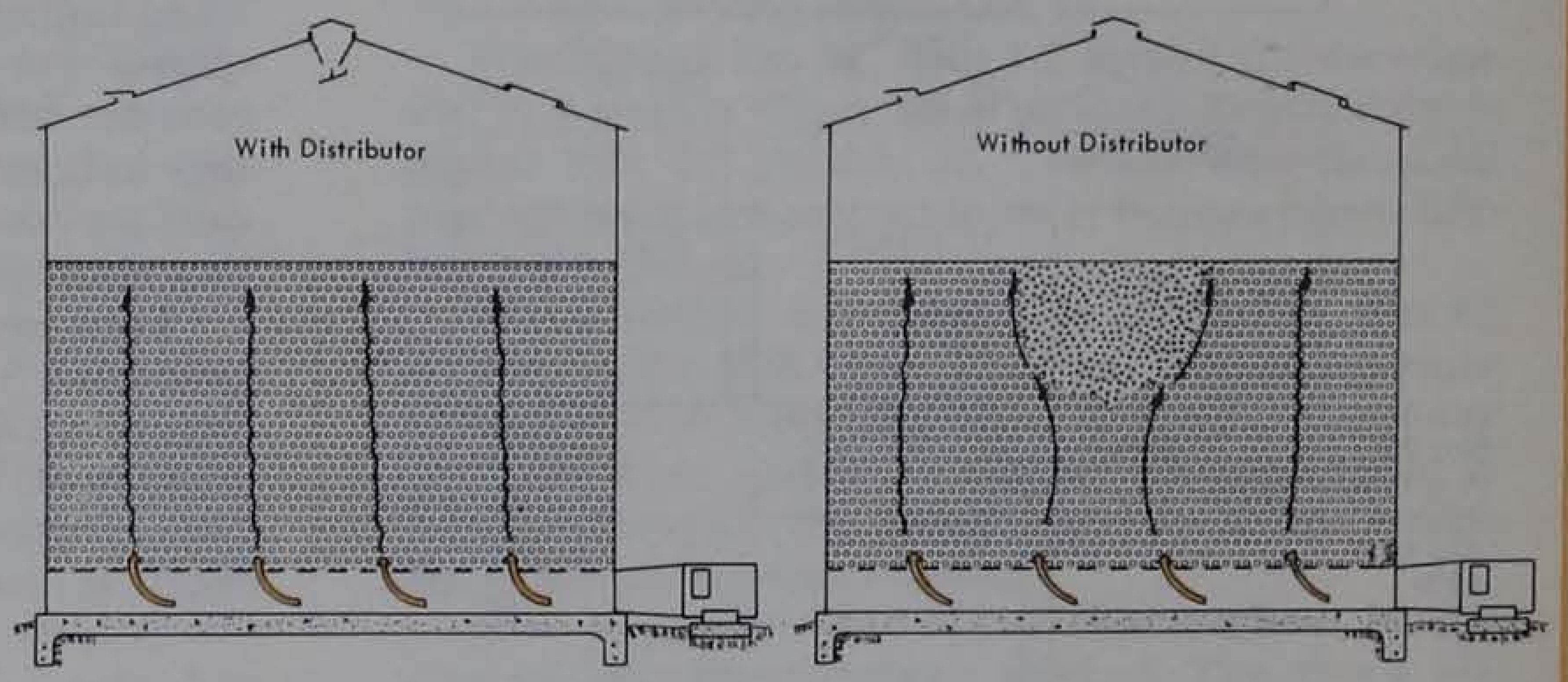
4a. Resistance depends on the type of grain. Larger grains like corn, soybeans, and sunflower seeds provide bigger open spaces between seeds and offer less resistance to airflow. Smaller grains like oats, rough rice, or wheat pack tighter in a bin and offer greater resistance.



4c. For the same amount of grain and cfm/bu, the larger diameter Bin A offers less resistance than the smaller diameter Bin B.



4b. Broken grain and foreign material increase resistance. They concentrate under the spout and reduce airflow to the "dirty" area. Clean the grain and use a spreader to minimize this problem.



4d. Resistance increases as grain is packed into a bin. A grain spreader may pack grain, but its advantage in spreading fines and leveling outweigh the disadvantage of packing.

Fig 4. Resistance characteristics of grain.

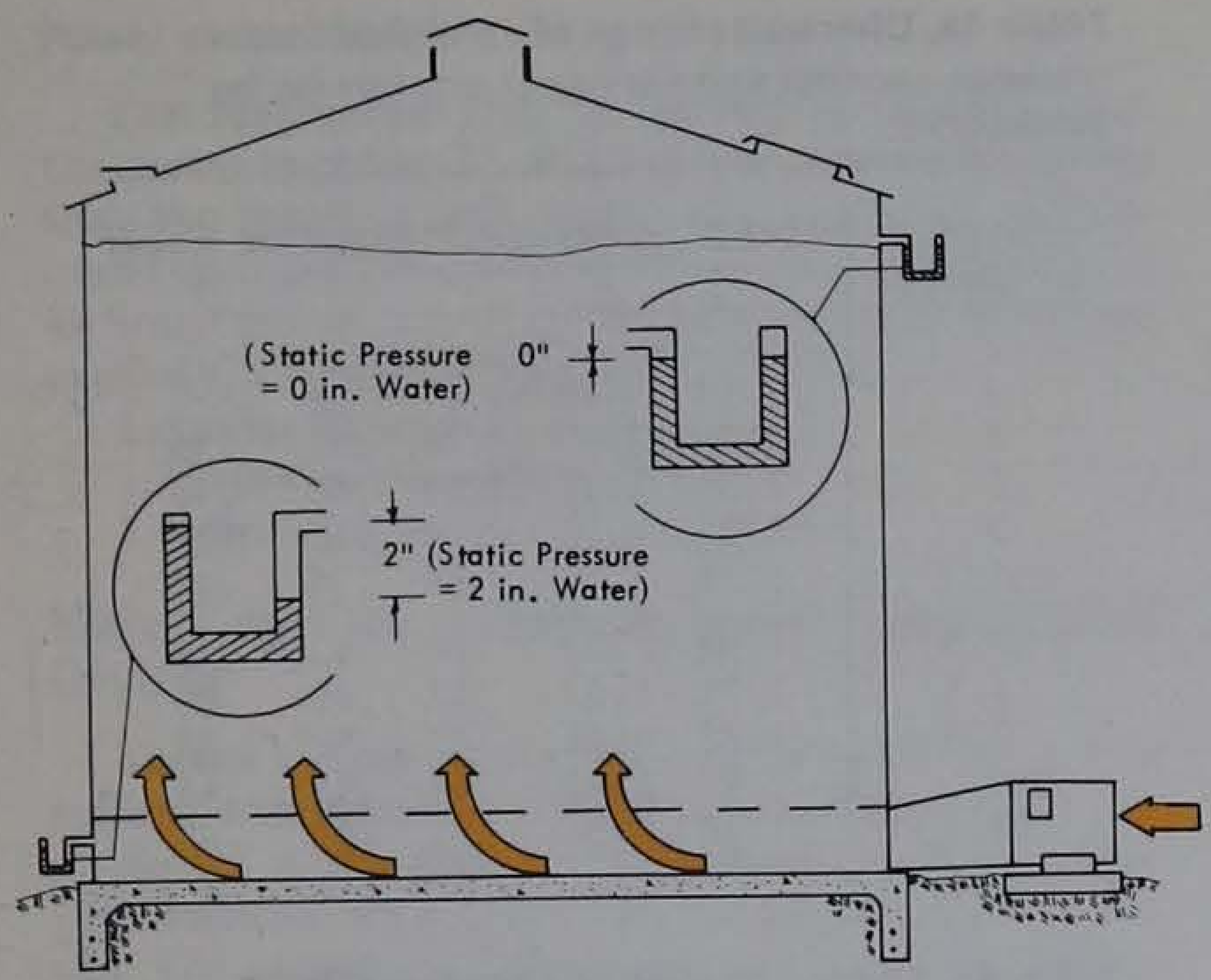


Fig 5. Measuring static pressure in a bin.

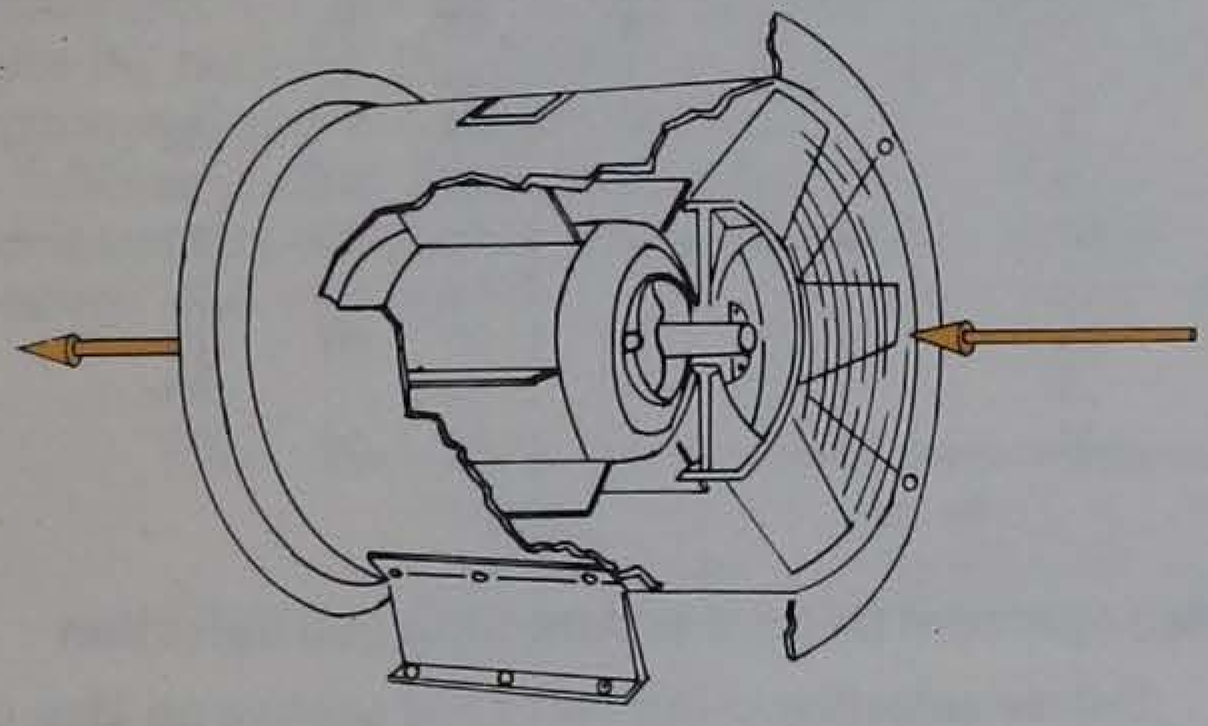


Fig 6. Axial-flow fan.

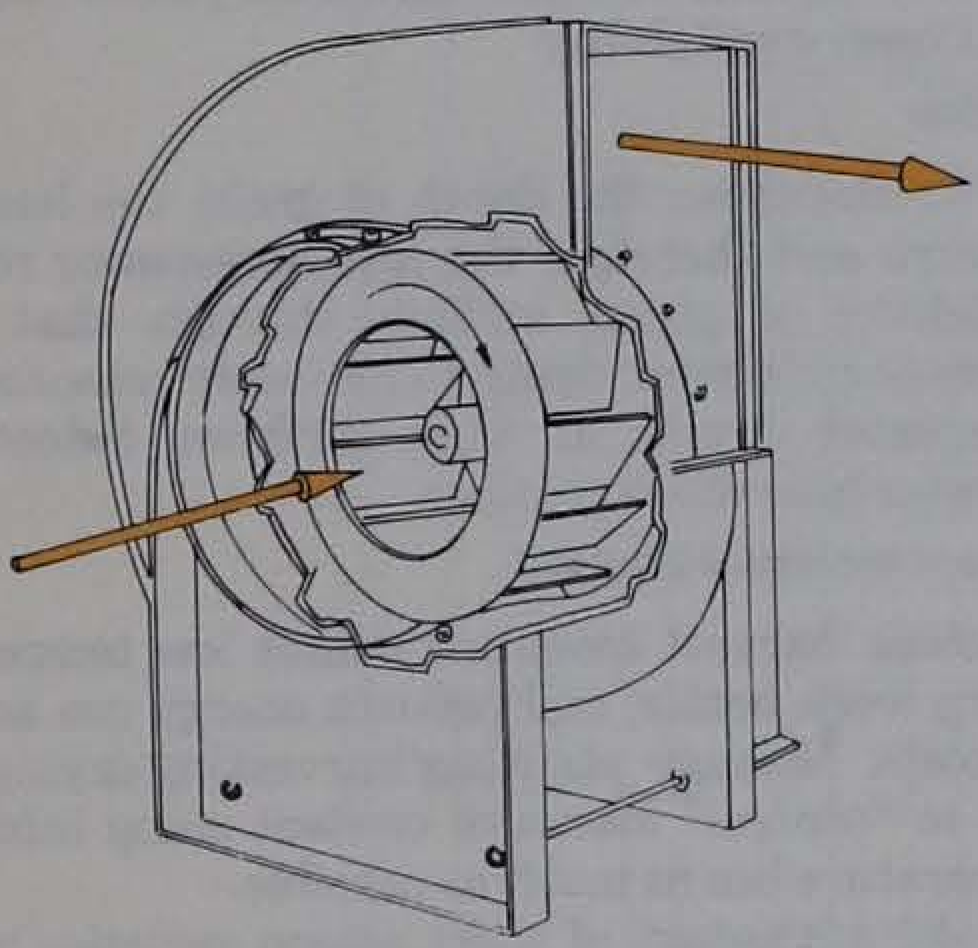


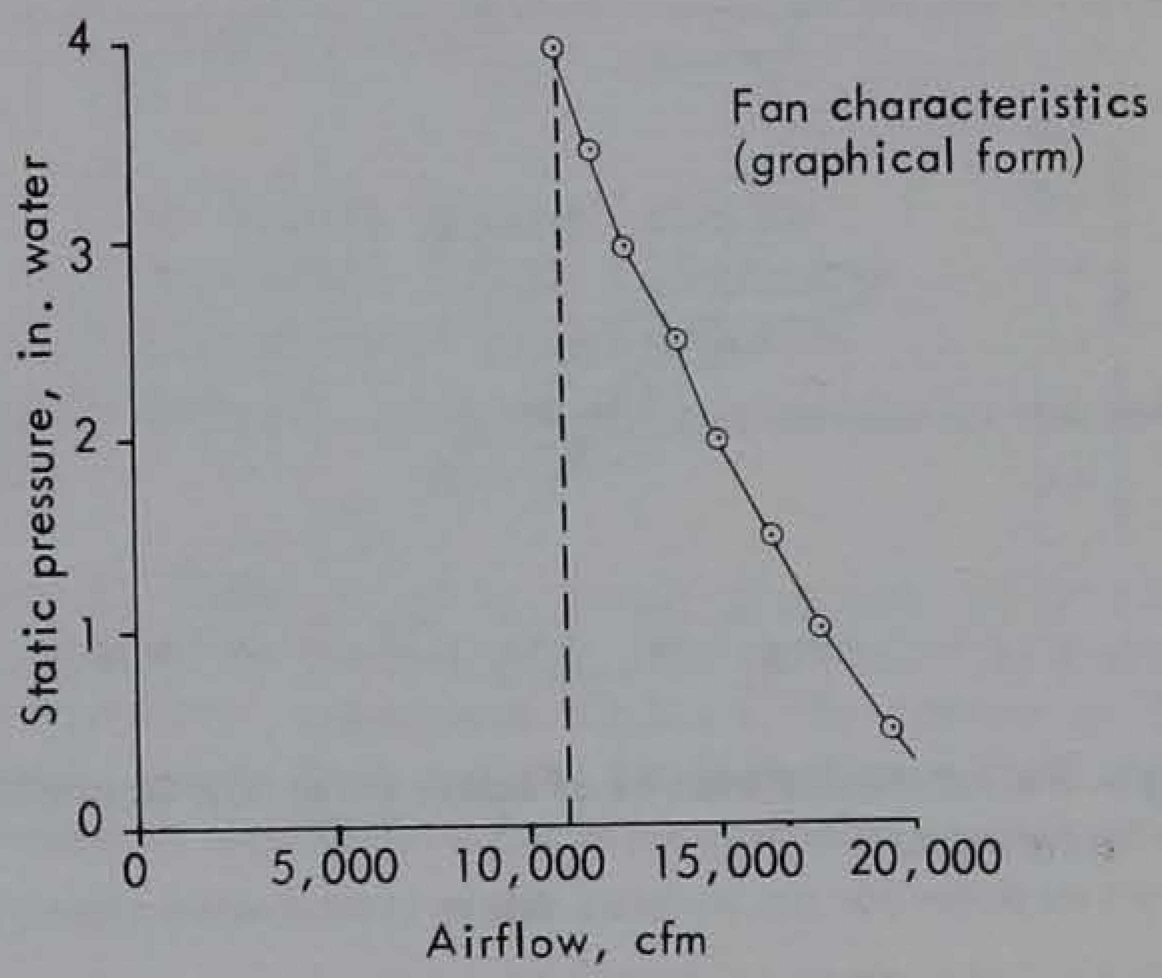
Fig 7. Backward-curved centrifugal fan.

Fan Performance

Fan performance is based on the airflow (cfm) a fan delivers at a given static pressure. Manufacturers provide fan performance data in graphical or tabular form, Fig 8.

Example 6. What is the total airflow delivered by the fan of Fig 8 at 4" of static pressure? Answer: about 10,900 cfm.

Laboratory tests predict better performance than installed fans can provide. Pick a fan that delivers about 25% more than the recommended airflow.



Fan characteristics (tabular form)

Static pressure inches of water	Airflow cfm
0.5	19,200
1.0	17,800
1.5	16,800
2.0	15,300
2.5	14,200
3.0	12,800
3.5	11,800
4.0	10,900

Fig 8. Fan characteristics, graphical and tabular forms.
Dashed line indicates example in text.

Fan size is designated by the horsepower (Hp) of the fan motor. But, don't buy a fan on the basis of Hp alone because output airflow for fans of the same Hp varies. Also, Hp gives little indication of the airflow delivered at a given static pressure. Fig 9 and 10 show the variation of some 10 Hp fans. Know the static pressure required for your system and compare performance data of several fans before selecting one. The section Matching Fan to Bin for Low Temperature Drying, gives more information on fan selection.

Rated Hp is not a good indicator of the power required to operate the fan motor, either. Most air-over fan motors (motors mounted in the airstream) operate above their rated Hp which means they draw more electricity than you would expect.

If possible, compare fans for **cfm/ watt** as well as airflow delivery. Cfm/ watt is a measure of a fan's electrical efficiency much like miles per gallon measures a car's fuel efficiency. Drying costs are directly related to cfm/ watt. The cost of drying with a fan that delivers 1 cfm/ watt is half the cost of drying with a fan that delivers only 0.5 cfm/ watt. Select an axial-flow fan that delivers at least 1 cfm/ watt at 3" of static pressure. A centrifugal fan should deliver at least 1 cfm/ watt at 4" of static pressure.

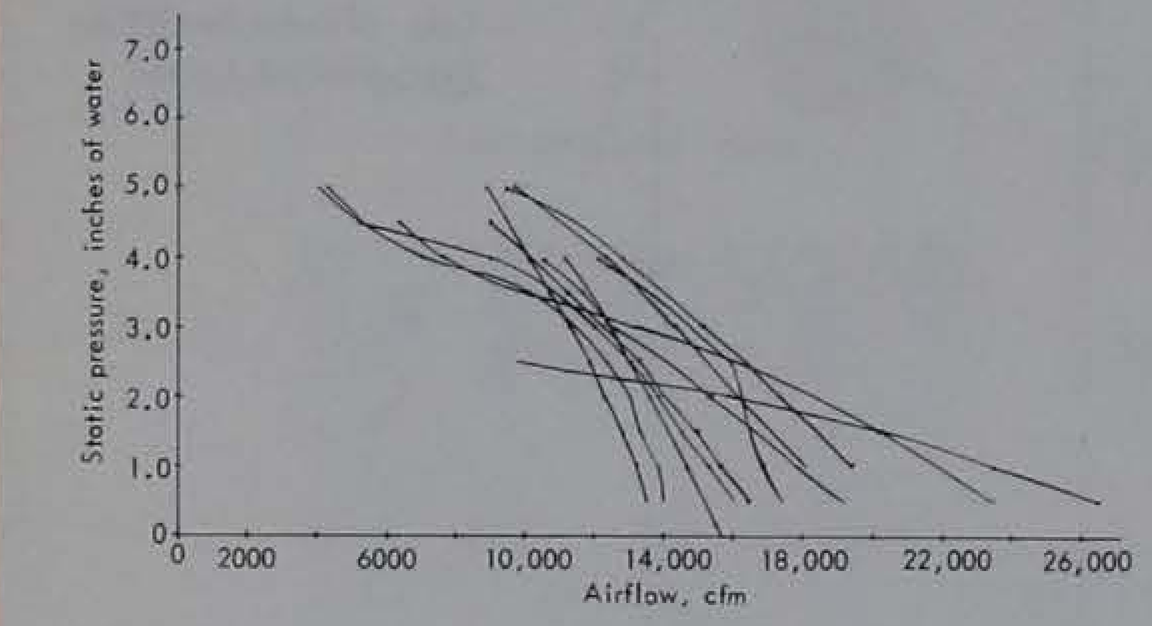


Fig 9. Performance curves of some axial-flow fans with 10-hp ratings.
Curves are plotted from manufacturers' data for 11 commercially available fans.

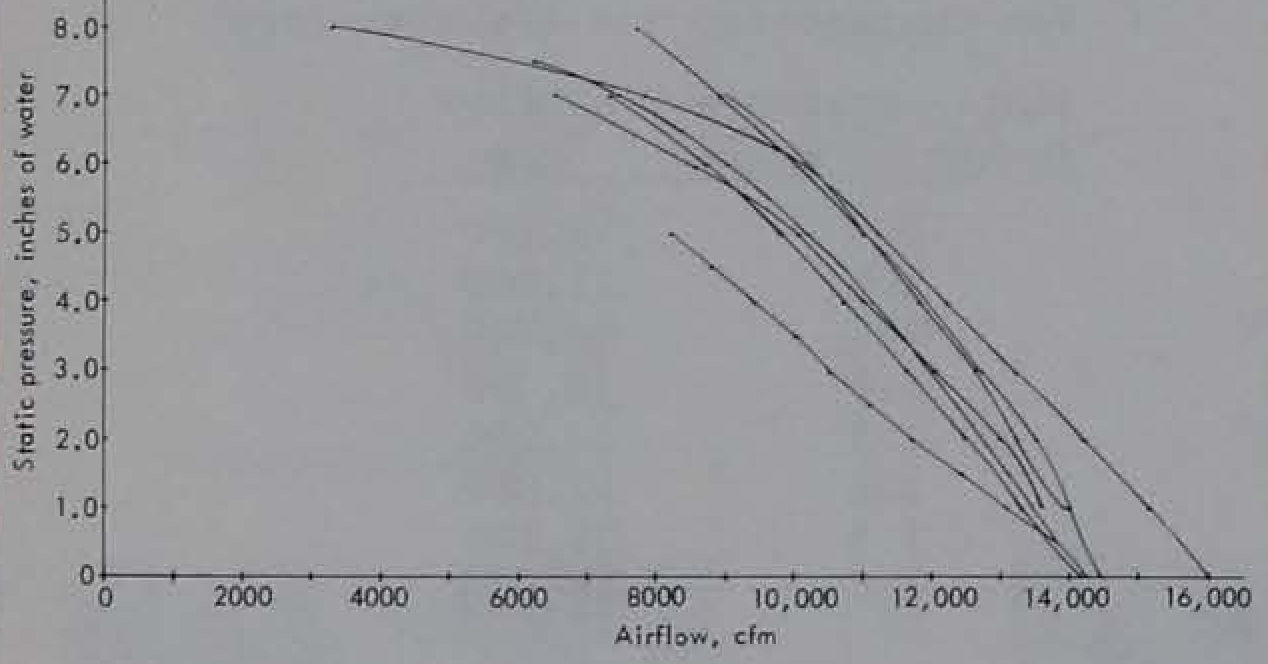


Fig 10. Performance curves of some centrifugal fans with 10-hp ratings.
Curves are plotted from manufacturers' data for 7 commercially available fans.

Table 4a compares cfm/ watt ratings of various axial-flow fans. It shows that cfm/ watt ratings:

- Can vary widely at the same static pressure.
- Always go down as static pressure goes up. (Keep static pressure as low as practical.)
- Are not necessarily better for larger Hp motors.

Centrifugal fans have similar variations, Table 4b.

Although cfm/ watt data for fans is seldom published, the manufacturer should have it. Insist the sales representative try to get this rating for you.

Table 4a. Cfm/watt ratings of axial-flow fans.
Efficiencies calculated from test data of fans from five fan manufacturers.

Rated	Static pressure, inches of water				
horsepower	2"	3"	4"	5"	6"
	- - - - -	cfm/watt	- - - - - -		
5	1.17	.88	.77	.58	
5	1.79	1.3	.76	.51	.36
5	1.82	1.37	1.08	.66	.53
5	1.35	1.04	.70	.46	.23
5	1.56	1.17	.88	.56	.29
7.5	.92	.77	.64	.53	.46
7.5	1.79	1.27	.72	.60	.26
7.5	1.38	1.11	.85	.58	.38
10	1.47	1.17	.88	.53	.41
10	1.78	1.36	.81	.47	.20

Table 4b. Cfm/watt rating of centrifugal fans.
Values calculated from test data of fans from five fan manufacturers.

Rated	Static pressure, inches of water				
horsepower	2"	3"	4"	5"	6"
	- - - - -	cfm/watt	- - - - -		
5	.97	.81	.71	.55	
7.5	.79	.70	.59	.50	
7.5	1.28		1.03		.82
10	.74	.57	.44	.41	.35
10	1.35	1.2	1.06	.93	.81
10	1.34		1.06		.82
15	1.28	1.16	1.05	.97	.87
15	1.33		1.04		.83
20	1.55	1.37	1.19	1.02	.91

Management Decisions Affecting Fan Selection

Before selecting a fan you need to have an idea of the following:

- Kind of grain and how much will be dried with low temperature
- Harvest capacity
- Bin size (diameter and depth) and static pressure
- Average harvest moisture from year to year
- Power availability

Bin size

The shallower the depth of grain, the less static pressure and therefore the less horsepower required to deliver a given airflow through that grain. Decrease maximum depth to maintain reasonable fan horsepower levels at high airflows. Select large diameter bins when possible.

Harvest moisture content

Lower harvest moisture makes low temperature drying work better, and reduces energy use and drying costs. Manage planting/ harvesting/ drying practices to "control" moisture content going into a low temperature bin as much as possible.

Take advantage of short season varieties to get a lower harvest moisture content. Some early-maturing varieties produce yields comparable to long-season varieties.

Power availability

Fan horsepower may be limited by the local electric power supplier. Find out the approximate fan size that the supplier will accept and the rates and demand charges. Shallower grain depths permit higher airflows per horsepower. At 1.25 Hp/1000 bu of bin capacity, a fan delivers about:

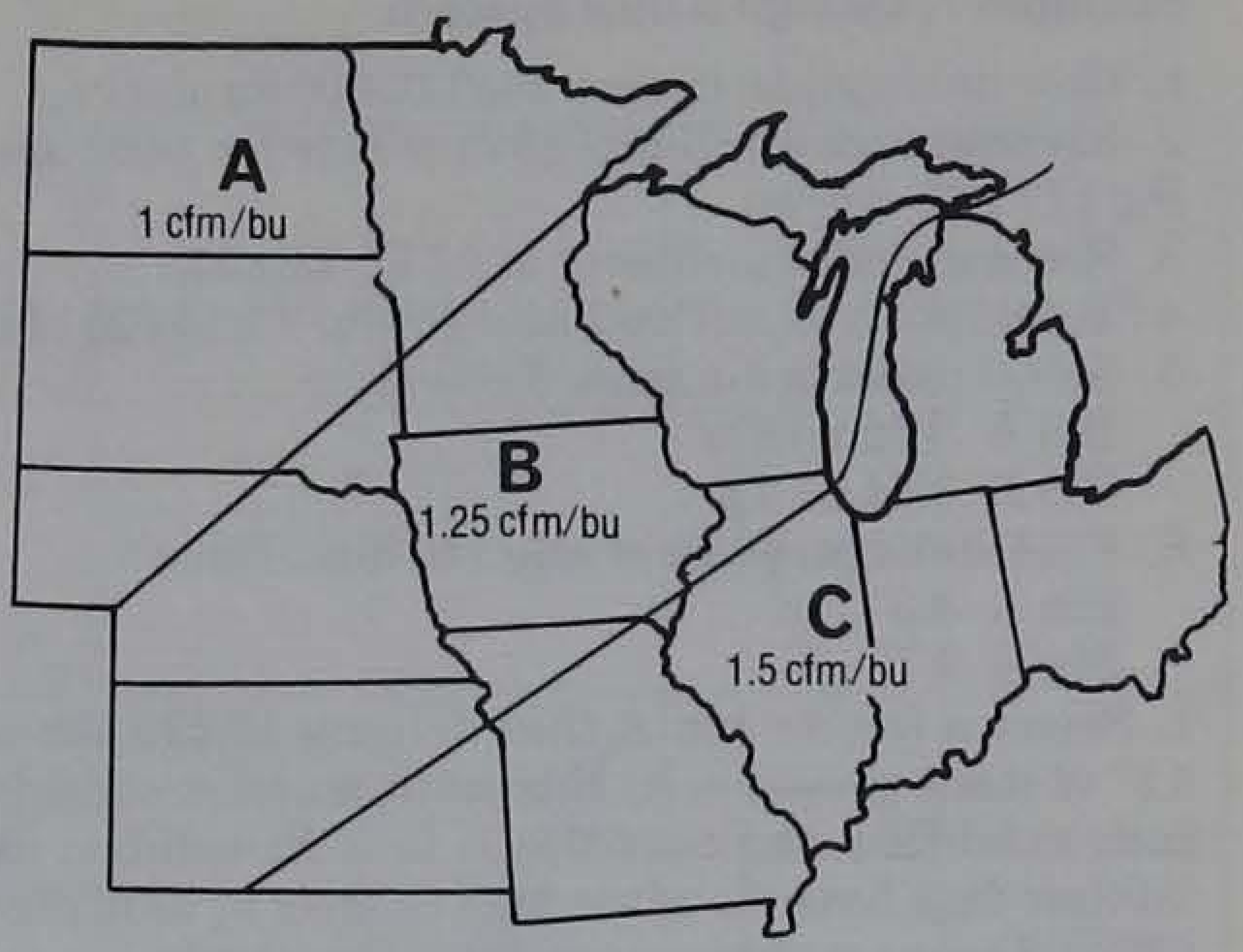
1 cfm/bu through 20' of corn
1.25 cfm/bu through 16' of corn
1.5 cfm/bu through 13' to 14' of corn

Matching Fan to Bin for Low Temperature Drying

Tables in this section help select a fan for a new system, and estimate airflow in an existing bin.

Select a fan that delivers the airflow given for your location in Fig 11. Provide more airflow if you can. The eastern and southern portions of the region need higher airflows because of higher humidities and somewhat warmer temperatures at harvest. If you follow the recommendations for bin filling and dryer management, you should be able to dry grain to a safe storage moisture content before the AST is exceeded. Do not try to dry grain with less than 1 cfm/bu because the airflow is not sufficient to cool grain and prevent major spoilage.

More airflow than the minimums in Fig 11 increases drying speed, gives an added margin of safety, and reduces the need to finish drying in the spring. Table 5 gives static pressure for various airflows and grain depths. Use this table as a guide to practical maximum airflows. To reduce drying costs, design your system for less than 4.5" of static pressure. See Table 6 for bin capacities.



A. Provide at least 1 cfm/bu
B. Provide at least 1.25 cfm/bu
C. Provide at least 1.5 cfm/bu

Fig 11. Recommended full-bin airflow rate for fan selection.

Table 5. Static pressures required for shelled corn.

This table is based on center filling or use of a drop-type distributor with wet shelled corn. With a sling-type distributor, multiply the static pressure by 1.3. With a sling-type distributor and a stirring machine, use static pressure values in the table.

Avoid static pressures above 5.0".

Grain depth ft	Airflow rate, cfm/bu 0.5	0.75	1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75	3.0
	static pressure, inches of water										
2							0.1	0.1	0.1	0.1	0.1
3			0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2
4		0.1	0.1		0.2	0.2	0.2	0.3	0.3	0.4	0.4
5	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.7
6	0.1	0.2	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
7	0.2	0.2	0.3	0.5	0.6	0.7	0.9	1.0	1.2	1.3	1.5
8	0.2	0.3	0.5	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.1
9	0.3	0.4	0.6	0.8	1.0	1.3	1.6	1.8	2.1	2.4	2.8
10	0.3	0.5	0.8	1.0	1.3	1.7	2.0	2.4	2.8	3.2	3.6
11	0.4	0.7	1.0	1.3	1.7	2.1	2.5	3.0	3.5	4.0	4.6
12	0.5	0.8	1.2	1.6	2.1	2.6	3.1	3.7	4.3	5.0	5.7
13	0.6	1.0	1.4	1.9	2.5	3.1	3.8	4.5	5.3	6.1	7.0
14	0.7	1.2	1.7	2.3	3.0	3.7	4.6	5.4	6.4	7.4	8.4
15	0.8	1.4	2.0	2.7	3.5	4.4	5.4	6.5	7.6	8.8	
16	0.9	1.6	2.3	3.2	4.2	5.2	6.4	7.6	8.9		
17	1.1	1.8	2.7	3.7	4.8	6.1	7.4	8.9			
18	1.2	2.1	3.1	4.3	5.6	7.0	8.5				
19	1.4	2.4	3.5	4.9	6.4	8.0	9.8				
20	1.5	2.7	4.0	5.5	7.2	9.1					

Axial fans: above solid line.
Centrifugal fans: below dashed line.

Example 7. Design a new system.

1. How much grain in each bin? 10,000 bu of corn
2. Recommended full-bin airflow rate for your area, Fig 11? 1.25 cfm/bu
3. Recommended airflow (1 x 2)? 12,500 cfm
4. Total required airflow? Add 25% to #3: 15,625 cfm
5. Select possible bin sizes, Table 6.
   Bin A 30'd x 18'h
   Bin B 33'd x 15'h
6. Find static pressure of selected bins, Table 5.
   Bin A 4.3"
   Bin B 2.7"
7. Select a fan for bin A that delivers 15,625 cfm at 4.3" of static pressure. At this static pressure consider both axial-flow and centrifugal fans. Remember, axial-flow fans have an advantage in layer or controlled filling. Compare cfm/watt ratings if available.
8. Repeat #7 for bin B. Select a fan that delivers 15,625 cfm at 2.7" of static pressure.
9. Compare possible fan/bin combinations for fan and bin costs, projected annual drying costs, and cfm/watt. Remember that shallow grain depths are better for low temperature drying. Also, consider dealer service and maintenance.

Example 8. Estimate full-bin airflow.

The bin is 30'd x 18'h, holds 10,000 bushels, and is equipped with a 10Hp fan.

1. Get fan performance data for your fan. Fig 12 is the fan curve for this example.
2. Calculate cfm/bu for several static pressures on the graph (or table): cfm/bu = airflow ÷ bin capacity; at 1" of static pressure, 17,800 cfm ÷ 10,000 bu = 1.78 cfm/bu.

Static pressure Fig 12	Total airflow Fig 12	Cfm/bu Fig 12
1"	17,800	1.78
2"	15,300	1.53
3"	12,800	1.28
4"	10,800	1.08

3. For about the same static pressures, find the approximate cfm/bu for the 18' deep bin. In Table 5, the 18' depth shows 1.1" of static pressure at 0.5 cfm/bu.

Static pressure Table 5	Cfm/bu Table 5
1.2	0.5
2.1	0.75
3.1	1.0
4.3	1.25

Table 6. Capacities of round bins.

This chart is based on 1 cu ft = 0.8 bu and does not involve test weight, moisture content, or shrinkage.

Grain depth						Bin diameter, ft						
ft	15	18	21	24	27	30	33	36	39	42	48	60
						- - - - bushels - - - -						
1	142	204	278	363	460	568	687	818	960	1113	1453	2271
2	284	409	556	727	920	1136	1374	1635	1919	2226	2907	4542
3	426	613	835	1090	1380	1703	2061	2453	2879	3338	4360	6813
4	568	818	1113	1453	1840	2271	2748	3270	3838	4451	5814	9084
5	710	1022	1391	1817	2299	2839	3435	4088	4798	5564	7267	11355
6	852	1266	1669	2180	2759	3407	4122	4905	5757	6677	8721	13626
7	994	1431	1947	2544	3219	3974	4809	5723	6717	7790	10174	15897
8	1136	1635	2226	2907	3679	4542	5496	6541	7676	8902	11628	18168
9	1277	1840	2504	3270	4139	5110	6183	7358	8636	10015	13081	20439
10	1419	2044	2782	3634	4599	5678	6870	8176	9595	11128	14535	22710
11	1561	2248	3060	3997	5059	6245	7557	8993	10555	12241	15988	24981
12	1703	2453	3338	4360	5519	6813	8244	9811	11514	13354	17441	27252
13	1845	2657	3617	4724	5978	7381	8931	10628	12474	14466	18895	29523
14	1987	2861	3895	5087	6438	7949	9618	11446	13433	15579	20348	31794
15	2129	3066	4173	5450	6898	8516	10305	12264	14393	16692	21802	34065
16	2271	3270	4451	5814	7358	9084	10992	13081	15352	17805	23255	36336
17	2413	3475	4729	6177	7818	9652	11679	13899	16312	18919	24709	38607
18	2556	3679	5008	6541	8278	10220	12366	14716	17271	20030	26162	40878
19	2697	3883	5286	6904	8738	10787	13053	15534	18231	21143	27616	43149
20	2839	4088	5564	7267	9198	11355	13740	16351	19190	22256	29069	45420

4. Plot the cfm/bu data on a graph as in Fig 13. The fan operates at the static pressure where the cfm/bu values are equal (the lines cross). The graph is actually a fan curve with airflow in cfm/bu. The example fan is operating between 1 and 1.25 cfm/bu (between 3" and 4" of static pressure).
5. Because this procedure only estimates airflow, round down. (Use 1 rather than 1.25 cfm/bu.) Assume the system operates at the lower airflow rate when planning a filling strategy.

Summary of Design Recommendations

- Equip bin with full perforated floor.
- Install a grain distributor.
- Provide a minimum of 1 cfm/bu.
- Provide roof openings of 1 sq ft/1000 cfm.
- Design for a static pressure of 4.5" or less.
- Limit bin depth to 20'; 14' or 15' is preferred.

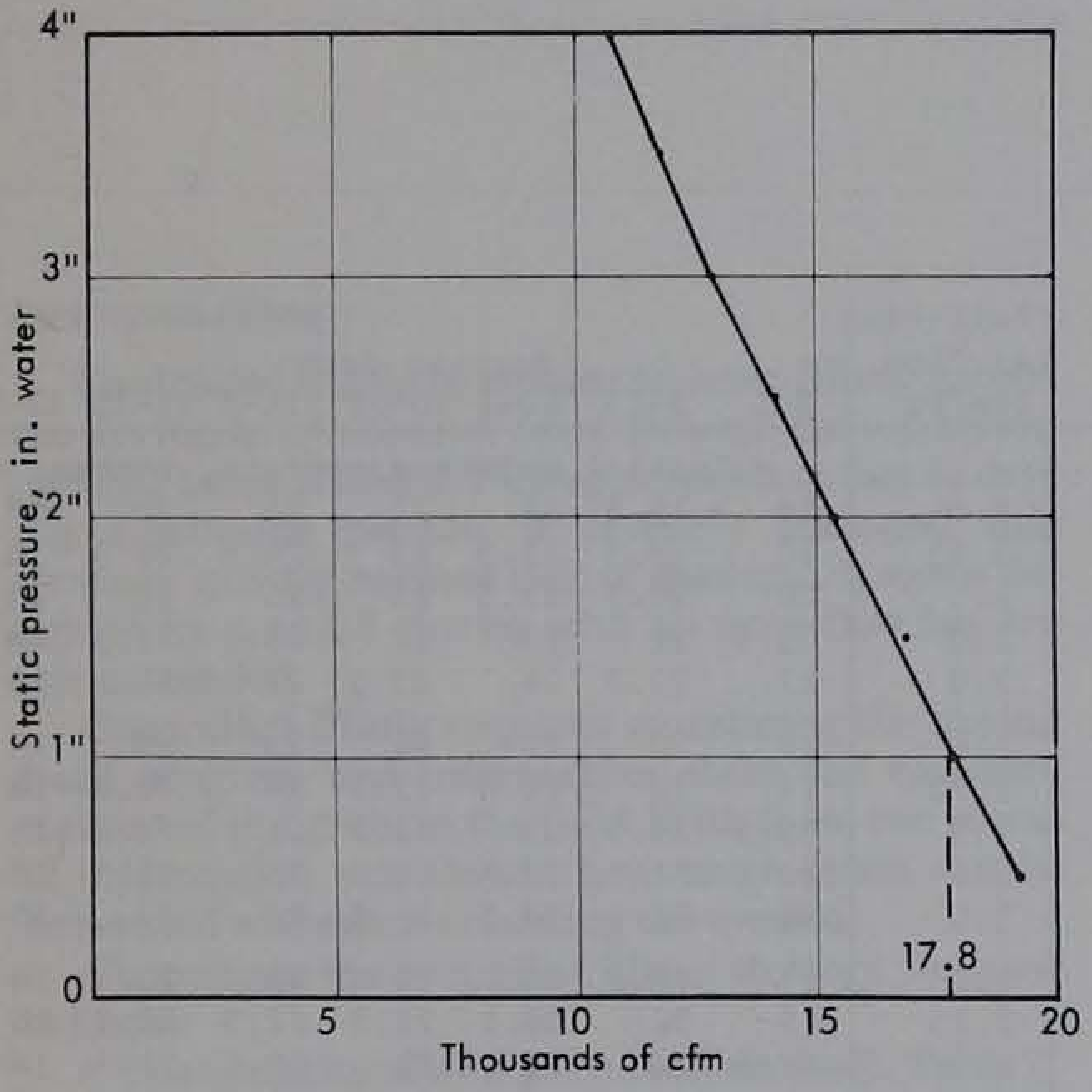


Fig 12. Performance data for fan of Example 8.
Dashed lines indicate example in text.

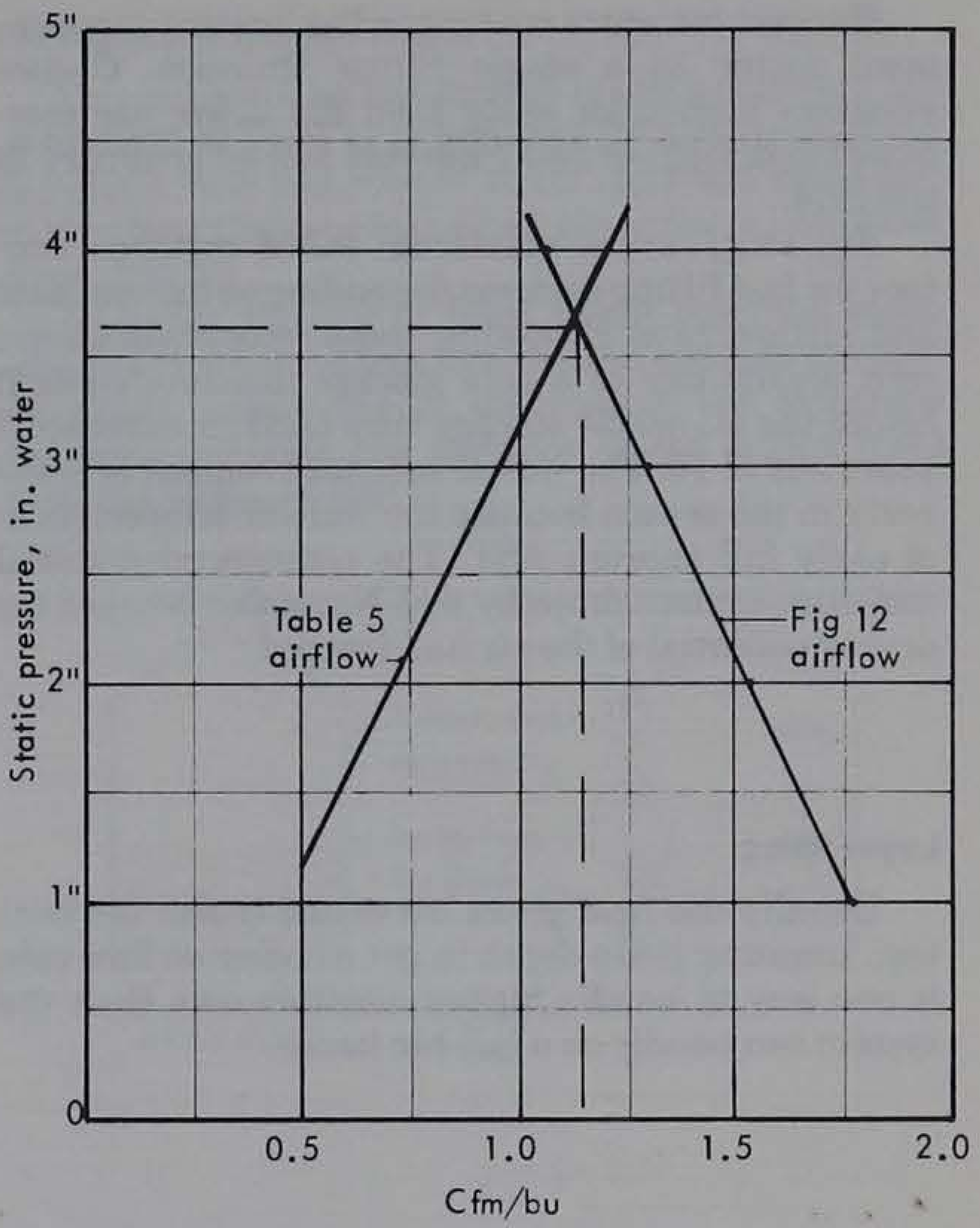


Fig 13. Estimating airflow for Example 8.
Lines cross at estimated airflow.

Managing a Low Temperature Dryer

Filling Strategies

Do not "overload" the system with wetter grain than it is designed to dry. If you do, the risk of spoilage increases sharply. Choose from 3 filling strategies to handle harvest moisture conditions for an individual year.

- **Single filling:** Sometimes called fast filling. The bin is filled in 1 to 3 days.
- **Layer filling:** Grain is added in layers over a period of time. There are two ways to decide when to add the next layer: **1)** Let the drying front come through before adding more, or **2)** Fill on a set time period (eg. weekly). Drying front may or may not be through the top. Layer filling is a safe way to dry corn, but can slow harvest when drying conditions are good, relative to controlled filling.
- **Controlled filling:** A method of managing layer filling. Harvest proceeds as fast as drying conditons permit because you don't wait for the drying front to come through the surface grain.

Single filling

Harvest moisture content is the limiting management factor in a single filling situation. Choose varieties known for early field dry down, use combination drying, or delay harvest and let grain dry in the field.

Fig 14 gives the maximum initial moisture content for fast filling systems depending on harvest date and airflow rate. Following these recommendations, corn should dry to a safe storage moisture content before the allowable storage time (AST) is exceeded 9 years out of 10. The initial moisture content is lower early in the season because the warmer temperatures of early fall shorten AST. The recommended initial moisture content drops by mid-November because the drying potential of the air has dropped.

Layer filling

Usually the first grain harvested is also the wettest. Limiting grain depth to get a higher airflow rate is one way to handle higher moisture corn than the system can handle on a full-bin basis.

Airflow is higher in a partially filled bin because of lower grain depth and static pressure. The actual airflow rate depends on individual fan performance, but in a bin designed for 1 cfm/bu on a full-bin basis, the airflow rate is at least 4 cfm/bu if the bin is 1/4 full (10,000 cfm ÷ 2,500 bu = 4 cfm/bu), Fig 15.

When layer filling, you load a fraction of the bin's capacity each week. While the first layer starts to dry in the bin, the standing corn continues to dry down in the field. The second layer needs less airflow when it is loaded into the bin.

The maximum moisture contents given in Fig 14 can be increased if you spread out filling. If you harvest grain wetter than the moisture limits of Fig 14, layer fill to compensate:

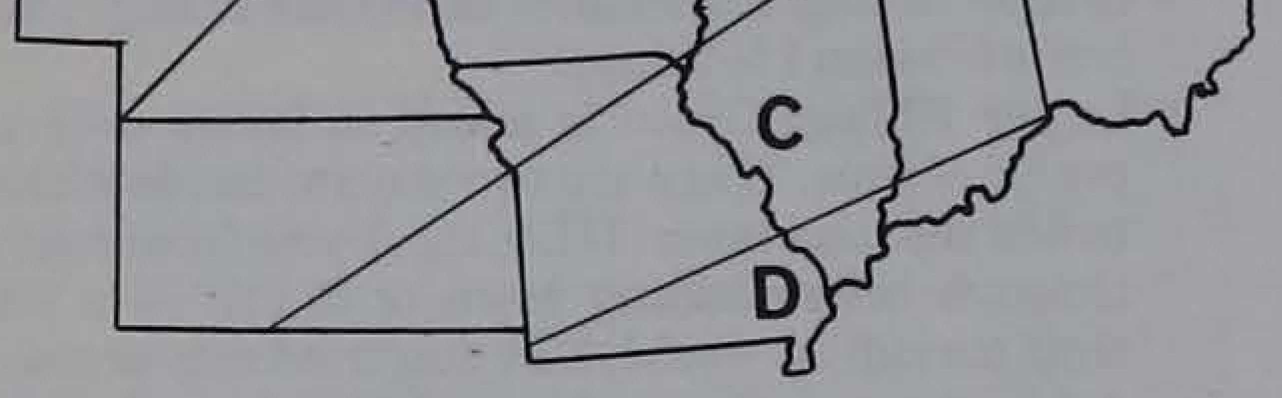
- Add grain every 5 to 7 days

Before Nov. 1:

- Add 1/4 of bin depth if 3 points too wet
- Add 1/3 of bin depth if 2 points too wet
- Add 1/2 of bin depth if 1 point too wet

After Nov. 1:

- Add 1/4 of bin depth if 2 points too wet
- Add 1/3 of bin depth if 1 point too wet



Zone	Full-bin airflow cfm/bu	Harvest date						
		9-1	9-15	10-1	10-15	11-1	11-15	12-1
		- - Initial moisture content, percent -						
A	1.0	18	19.5	21	22	24	20	18
	1.25	20	20.5	21.5	23	24.5	20.5	18
	1.5	20	20.5	22.5	23	25	21	18
	2.0	20.5	21	23	24	25.5	21.5	18
	3.0	22	22.5	24	25.5	27	22	18
B	1.0	19	20	20	21	23	20	18
	1.25	19	20	20.5	21.5	24	20.5	18
	1.5	19.5	20.5	21	22.5	24	21	18
	2.0	20	21	22.5	23.5	25	21.5	18
	3.0	21	22.5	23.5	24.5	26	22	18
C	1.0	19	19.5	20	21	22	20	18
	1.25	19	20	20.5	21.5	22.5	20.5	18
	1.5	19.5	20	21	22	23.5	21.5	18
	2.0	20	21	22	23	24.5	21.5	18
	3.0	21	22	23.5	24.5	25.5	22	18
D	1.0	19	19.5	20	21	22	20	18
	1.25	19	19.5	20.5	21	22.5	20.5	18
	1.5	19	19.5	21	22	23	21	18
	2.0	19.5	21	21.5	23	24	21.5	18
	3.0	20.5	21.5	23	24	25	22	18

Fig 14. Maximum corn moisture contents for single-fill drying.
Developed by Thomas L. Thompson

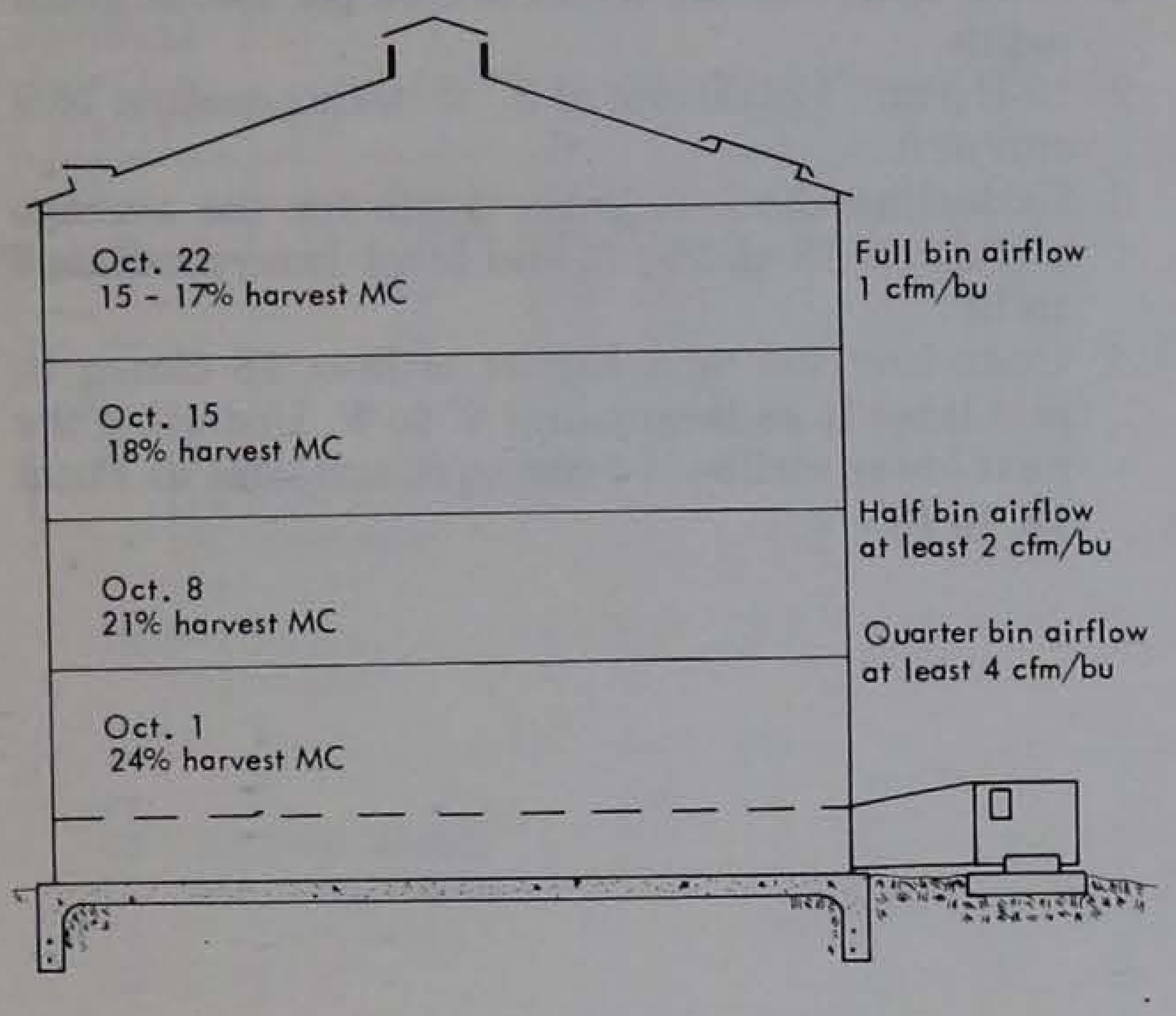


Fig 15. Example of layer filling.
The higher airflow rates early in the filling permit a higher initial moisture content to be loaded.

Controlled filling*

Controlled filling is similar to layer filling except the drying front does not come through the top before another layer is added. Filling proceeds as fast as drying conditions permit. If properly managed this strategy greatly reduces risk of spoilage. Systems designed for 1 to 1.5 cfm/bu with an axial-flow fan are recommended.

Controlled filling requires monitoring the drying front progress and information about the moisture content of the grain in the field. With these two pieces of information you decide how much grain can be harvested without overloading the system.

To manage the controlled filling strategy you need to know:

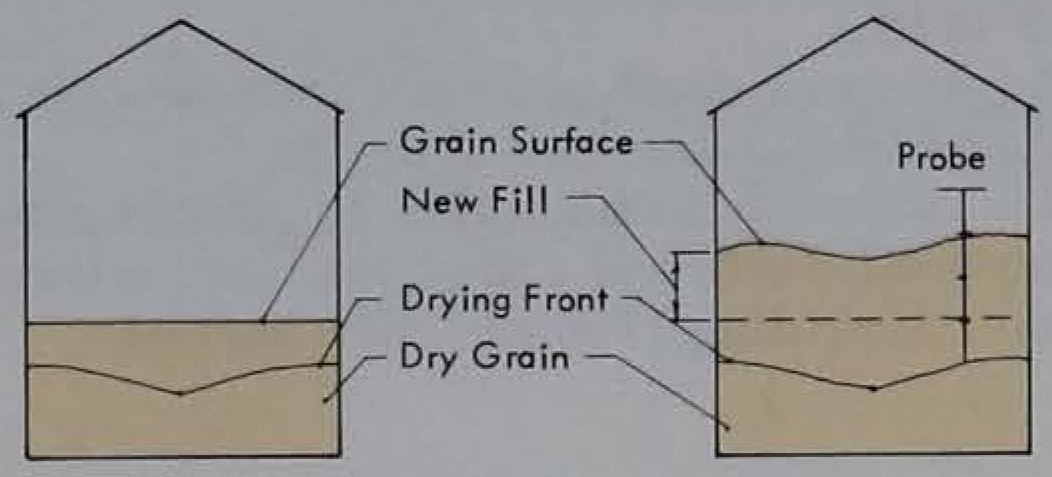
- The quantity of corn per foot of bin depth, Table 7.
- The amount of airflow in each bin in cfm/sq ft, Table 7.
- The moisture content of the grain in the field. A portable moisture meter is accurate enough.
- The maximum safe depth of wet corn, Table 8.
- Rules of controlled filling, Table 9.
- Progress of the drying front. See "Locating the Drying Front", below.

Tables 7 to 10 explain how controlled filling works. Once you understand the filling procedure, you need only Tables 8 and 9.

Locating the Drying Front

You can walk on the surface of wet grain (20% mc or higher); at most your feet sink 2" to 3". In a bed of dry grain your feet sink 5" to 10". It is this difference in firmness that you feel when using the drying front probe, Fig 16.

To locate the drying front slowly push the probe into the grain until you feel the end slip into the drying front. Using the 2' spacings of the extension couplers, estimate the distance to the drying front from the grain surface.



Shape daily fill away from deep pockets for more uniform drying.

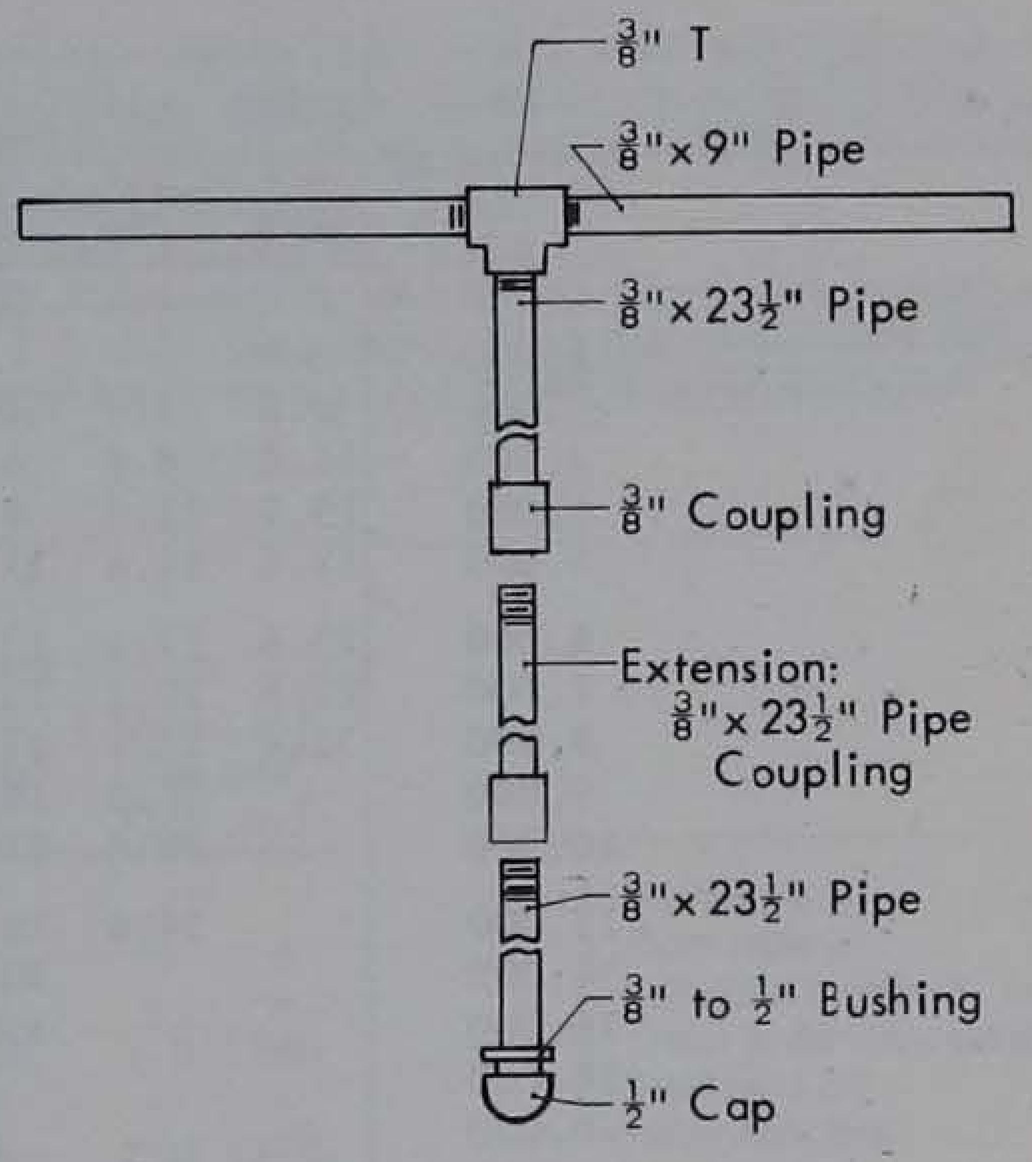


Fig 16. Grain drying-front probe.

Progress of the drying front may not be uniform throughout the bin because of fines accumulation and reduced airflow. Often it moves slower through the center of the bin. Probe several areas of the bin at least once a week to be sure you find the deepest area of the front. During filling, you can vary the thickness of a layer slightly to encourage uniform progress of the front.

*Developed from ASAE paper 79-3032, Van Ee and Kline.

Planning Before Harvest

1. Determine quantity of grain per foot of bin depth. Table 7.
2. Determine total airflow rate at 3" of static pressure for each fan. See manufacturer's data. Then, from Table 7, figure cfm/sq ft for each fan.
3. Mark the performance of your system on Table 8. This estimates system performance for the intermediate stage of drying when grain depth is 6' to 12' (static pressure is about 3").
4. The next higher level of airflow rate on Table 8 estimates system performance in the beginning stage of filling 0' to 6'. And, the next lower level of airflow estimates performance in the final stages, 12' to 18'.
5. Paint a grain depth scale in 1' increments in 2 or 3 places around the inside of the bin.
6. You are ready to fill. Table 10 outlines a typical harvest/fill schedule and shows how the 6 rules of controlled filling (Table 9) affect harvest.

Example 9. Planning for controlled filling.

1. A 30' diameter bin holds 570 bu per foot of grain depth.
2. 10 Hp fan, 12,000 cfm at 3" of static pressure: 16.9 cfm/sq ft
3. Underline the wet grain depth for the average airflow of 16 cfm/sq ft and label **Intermediate 6' to 12'**.
4. Underline the next higher airflow, 18 cfm/sq ft, and label it as **Beginning 0' to 6'**. Underline the next lower airflow, 14 cfm/sq ft, and label as **Final 12' to 18'**.

Table 7. Bin capacity (bu/ft of depth) and average airflow (cfm/ft^2).
Dashed lines indicate examples in text.

	Bin diameter, ft.								
Fan discharge cfm	18	21	24	27	30	33	36	42	48
	Quantity of corn, bu/ft								
	200	280	360	460	570	690	820	1110	1450
	Average airflow, cfm/sq ft								
1,000	3.9								
2,000	7.8	5.7	4.4						
3,000	11.8	8.6	6.6	5.2	4.2				
4,000	15.7	11.5	8.8	7.0	5.6	4.6	3.9		
5,000	19.6	14.4	11.0	8.7	7.0	5.8	4.9	3.6	
6,000	23.6	17.3	13.2	10.4	8.5	7.0	5.9	4.3	
7,000	27.6	20.2	15.4	12.2	9.9	8.1	6.9	5.0	3.8
8,000	31.4	23.1	17.6	13.9	11.3	9.3	7.8	5.7	4.4
9,000		26.0	19.8	15.7	12.7	10.5	8.8	6.5	4.9
10,000		28.8	22.1	17.4	14.1	11.7	9.8	7.2	5.5
12,000		34.6	26.5	20.9	16.9	14.0	11.7	8.6	6.6
14,000			30.0	24.4	19.8	16.3	13.7	10.1	7.7
16,000			35.3	27.9	22.6	18.7	15.7	11.5	8.8
18,000				31.4	25.4	21.0	17.6	13.0	9.9
20,000				34.9	28.3	23.3	19.6	14.4	11.0
22,000					31.1	25.7	21.6	15.8	12.1
24,000					34.9	28.0	23.6	17.3	13.2
26,000						30.4	25.5	18.7	14.3
28,000						32.7	27.5	20.1	15.4
30,000							29.4	21.6	16.5
34,000							33.4	24.5	18.7
36,000								27.4	20.1
42,000								30.3	23.2
46,000									25.4
50,000									27.6
54,000									30.9

Table 8. Maximum wet grain depth above the drying front.

Dashed lines indicate examples in text.

Average airflow cfm/ft^2	18	19	20	21	22	23	24	25	26
	- - - - Max. wet grain depth, ft - - - - -								
6	15	7.5	5.0	3.7	3.0	2.5	- Don't fill		
8		10	6.6	5.0	4.0	3.3	2.5	2.0	
10		12	8.3	6.2	5.0	4.1	3.1	2.5	2.1
12		15	10	7.5	6.0	5.0	3.7	3.0	2.5
14 Final (12'-18')		18	11	8.7	7.0	5.8	4.4	3.5	2.9
16 Intermediate (6'-12')			13	10	8.0	6.6	5.0	4.0	3.3
18 Beginning (0'- 6')			15	11	9.0	7.5	5.6	4.5	3.7
20			17	13	10	8.3	6.2	5.0	4.1
24				15	12	10	7.5	6.0	5.0
28 20 feet depth				17	14	11	8.7	7.0	5.8
32 max. recommended					16	13	10	8.0	6.6
36					18	15	11	9.0	7.5
40						17	12	10	8.3

Incoming grain moisture, percent (columns 18–26).

Table 9. Rules for controlled filling.

Rules 4 and 5 must both be met before more grain filling is allowed.

1. Begin harvest as soon as the corn moisture in the field is 26% or less.
2. For corn 24% to 26% moisture content, the maximum daily filling depth is 2'.
3. For corn less than 24% moisture content, the maximum filling depth is 4'.
4. For corn 22% moisture content and higher, the initial drying front must be at least halfway up the grain profile before you can add more wet grain.
5. For all incoming corn moistures, the filling depth may not exceed the maximum recommended wet grain depth, Table 8.
6. Controlled filling may be skipped on any day the quantity allowed is too small to be practical or other harvest activities take precedence.

Table 10. Example of controlled filling.

Oct. 10: corn moisture 26%; harvest begins (Rule #1). Table 8 shows that in the beginning stage of filling, the example bin can handle 3.7' of wet grain, but Rule #2 controls and reduces fill to 2'.
Oct. 11: corn moisture 25.5%; drying front must be halfway through the grain that is in the bin (Rule #4). It is not; do not fill.
Oct. 12: corn moisture 25%; drying zone is halfway through grain profile. Add 2'.
Oct. 16: corn moisture 23%; maximum daily fill is 4' if drying zone is halfway through existing grain. Table 8 shows 6.6' is the maximum depth of wet grain allowed. 3.6' is added (6.6' - 3' = 3.6'). 4' maximum is not violated.
Oct. 19: corn moisture 21.5%; maximum wet grain depth (Table 8) is 9'; probing shows 5.1' of wet grain is already in the bin; add 3.9' (Rule #5).
Oct. 20: corn moisture 21%; 8.5' of wet grain in the bin, can have maximum of 8.7'. Choose not to fill (Rule #6).
Oct. 23: filling completed after 14 days.
Nov. 11: drying completed after 33 days. During the early stages of filling, Rules 2, 3, and 4 usually control. During intermediate stages, Rules 4 and 5 usually control. For the final stage of filling, Rule 5 usually controls.

Date	Grain moisture in field percent	Bin condition, beginning of day: Total grain bu	Grain depth ft	Dry front position ft	Depth of wet grain ft	Max. wet grain depth^a ft	Quantity to add ft^b	bu^c
Beginning								
Oct. 10	26.0					–	–	–
Oct. 11	25.5	1140	2.0	0.5	1.5	4.1	–	–
Oct. 12	25.0	1140	2.0	1.0	1.0	4.5	2.0	1140
Oct. 13	24.5	2280	4.0	1.5	2.5	5.1	–	–
Oct. 14	24.0	2280	4.0	2.0	2.0	5.6	2.0	1140
Oct. 15	23.5	3420	6.0	2.5	3.5	6.5	–	–
Intermediate								
Oct. 16	23.0	3420	6.0	3.0	3.0	6.6	3.6	2052
Oct. 17	22.5	5472	9.6	3.5	6.1	7.3	–	–
Oct. 18	22.0	5472	9.6	4.0	5.6	8.0	–	–
Oct. 19	21.5	5472	9.6	4.5	5.1	9.0	3.9	2223
Final								
Oct. 20	21.0	7695	13.5	5.0	8.5	8.7	0.2^d	–
Oct. 21	20.5	7695	13.5	5.5	8.0	9.8	1.8	1026
Oct. 22	20.25	8721	15.3	6.0	9.3	10.4	1.1^d	–
Oct. 23	20.0	8721	15.3	6.5	8.8	11.0	2.2	1254
Oct. 24	*	9975	17.5,full	7.0	10.5	*	*	*
Oct. 25	*	9975	17.5	7.5	10.0	*	*	*
Oct. 26	*	9975	17.5	8.0	9.5	*	*	*
.	.	.	.	.	.	.	.	.
Nov. 11		9975	17.5	17.5	- - Drying completed - - -			

a. From Table 8.
b. From Table 9.
c. Calculated from bu/ft, Table 7.
d. Chose to disregard increments less than 1.5 ft.
* Filling completed.

Combination Drying

Combination drying fits with all three filling strategies, but is particularly helpful when using single or layer filling because of their initial moisture content limitations. Combination drying uses a high temperature dryer to dry to the moisture content the system can handle. Any type of column dryer, or a bin equipped with a stirring machine and heat can be used.

Fan Management

Regardless of filling strategy, follow the fan management practices given below. Do not shut off the fan during periods of high humidity, or foggy or rainy days. Air movement cools and controls heating of the grain even if drying slows. It also equalizes moisture differences (top to bottom).

Fall Drying

Turn on the fan(s) as soon as grain covers the floor of the bin. **Do not** turn the fan(s) off until one of the following occurs:

- Complete drying: all grain in the bin is dried to 15.5% moisture content or less. Aerate to cool for winter storage and to maintain quality.
- Late in the season if the drying zone is through the top and the moisture content is 18% or less. Begin aeration and winter management. Plan to spring dry.

Aeration

Aeration controls grain temperature to prevent or reduce spoilage. Aeration is not drying although small moisture changes do occur with a change in temperature.

Aerate to cool stored grain in the fall so there is no warm grain mass in the bin. Aerate to warm grain in the spring if storage is to be continued into the summer.

During aeration (cooling or warming), a tempering zone moves through the grain, much like the drying front during drying but much faster. Estimate the time required to move a cooling or warming front through the grain from Table 11. Usually 2 or 3 aeration periods are needed in the fall, unless drying lasts through November, and again in the spring.

Aerate when relatively dry weather is predicted. Operate the fan continuously until the cooling or warming front has moved through all the grain. Then, turn off the fan until:

- Another aeration period is needed.
- It is turned on for inspection, see Observation.
- Signs of heating are noticed. Run the fan until all signs of heating are gone.

Use temperature to know when the cooling or warming front is through the grain. Insert a thermometer 6" to 12" into the grain at the top of the bin. Turn off the fan when the temperature of the grain is about the same as the outdoor air temperature.

If cooling takes much longer than predicted in Table 11, either airflow is less than you thought, or fines are blocking airflow. Once you establish the time for one aeration period, it will take about the same time to move a temperature change through that depth of grain for the same bin and fan equipment.

For a more complete discussion, see Managing Dry Grain in Storage , AED-20, a Midwest Plan Service publication.

Table 11. Approximate grain cooling and warming times.

Times are based on 60-lb bushels in the Midwest and 10F to 15F temperature changes.
Hours per cfm/bu are: 15 (fall), 20 (winter), 12 (spring).

Airflow rate cfm/bu	Fall cooling hours	Winter cooling hours	Spring warming hours
1	15	20	12
1¼	12	16	10
1½	10	14	8

Cooling Grain for Winter Storage

Aerate to cool the grain for winter storage. Cool to 25 F to 30 F in North and South Dakota and in Minnesota; 30 F to 40 F elsewhere in the north central region. Start an aeration period whenever the average day-night temperature is 10 F to 15 F cooler than the grain. Typically, one to two weeks after cooling, outdoor temperatures will have dropped another 10 F to 15 F, so cool again.

Cooling to below freezing is not needed for grain that is properly dried, aerated, and managed. Frozen grain may be more difficult to warm in the spring.

Winter Management

- Check grain for signs of spoilage and/or heating. Turn on fan immediately if heating is detected. Run until all signs of heating, both in exhaust air and grain mass, have disappeared. See section on Observation.
- If grain moisture content is 15.5% or less, follow suggestions in AED-20.
- If grain moisture content is between 15.5% and 18%, run the fan 4 to 8 hours every week.

Spring Aeration and Drying

Inspect grain weekly during the spring, while temperatures are rising fairly rapidly.

If grain will be stored into summer, start warming when average air temperatures are 10 F to 15 F warmer than the grain. Estimate warming time from Table 11. Push the warming front through the grain with continuous fan operation, selecting a time for which relatively dry weather is forecast. Warm again if needed to bring grain temperature up to 50 F to 60 F.

If spring drying is needed, start the fan when outdoor temperatures average 40 F to 45 F and run continuously until top grain is at 15.5%. Because overdrying is difficult to avoid in the spring, average grain moisture content will likely be 13% to 14%.

Observation

Careful observation is the best way to detect unfavorable storage conditions. Check the grain once a week in fall, spring and summer, and every other week in the winter. Turn on the fan for about 20 minutes while checking grain condition. Climb into the bin to:

- **Smell:** A faint musty odor is the first indication that "something is happening". An odor is evident before heating, dark kernels, or spoilage occur. Smell is the most reliable signal in the spring when it is difficult to tell if grain is heating from mold growth or warming with spring.
- **Poke:** Use a 3/8"smooth steel rod to detect hard compact layers of grain that indicate spoilage.
- **Probe:** Take moisture samples from several locations. Differences of 1 to 2 points indicate potential problems. Run one complete cooling cycle and probe again.
- **Check for hot spots:** Keep a log of grain temperatures. A gradual increase in temperature may indicate heating and potential spoilage. Hotspots can occur anywhere in the bin, but for early detection, place thermometers, either cables with thermocouples or temperature probes, in three locations:

  Center: Fines collect in the center of the bin, especially if there is no distributor. Fines also provide favorable conditions for mold growth. A thermometer in the center warns you of heating early.

  North/northwest: This side of the bin is a likely place for a hot spot to generate. Insert a thermometer 1.5' deep and 4' to 5' from the bin wall. Watch this thermometer in the spring too. Spring temperatures revive mold.

  South/southwest: A thermometer is particularly useful here if you use an in-bin dryer with a stirring device. Grain at the outside wall may not dry and it can spoil from the heat of a southern exposure. If you overwinter grain at moisture contents greater than 15.5% the same holds true. Place a thermometer 6' to 8' deep and within 3' of the bin wall.

Handling Wet Corn in the Wet Season

An unusually wet fall, when grain does not dry down in the field, presents some problems for low temperature drying. Drying potential of the air is low because it is damp. Increasing drying potential with supplemental heat helps little in this type of drying season. Often, drying cannot be finished in the fall (corn moisture to 18% or less). Some options for handling wet grain in the wet season are:

- Use a high temperature dryer to predry to a moisture content your system can handle.
- Feed or sell the grain at harvest.
- Cool and hold the wet grain with aeration. Feed or sell it within the allowable storage time.
- If the grain is above 20%, mix it with dry grain so that grain moisture averages less than 18% and aerate to assure uniform grain temperature throughout the bin.

Summary of Management Tips

- Clean grain to reduce resistance to airflow and improve storability.
- Use grain distributor to spread remaining fines and foreign material, and to improve uniformity of airflow.
- Keep grain level to promote uniform progress of drying front.
- Start fan as soon as bin floor is covered.
- Open all roof hatches and vents when drying to provide adequate escape for exhaust air.
- Run fan continuously until drying is completed, or until average daily temperature is consistently below freezing.
- Cover fans when not in use to prevent air currents through the bin.
- Check grain periodically for signs of heating and/or spoilage.

Supplemental Heat

The drying ability in a low temperature dryer comes mainly from the air, not the added heat as in a high temperature dryer. If adequate airflow is provided through fan size and/or layer filling, corn dries to a safe moisture content for winter storage almost every year by the end of fall. Spring drying is necessary many years to reach a moisture content for safe long term storage.

By adding supplemental heat you cannot decrease the recommended airflow or load the system with wetter corn than recommended, nor will the grain dry much faster. Supplemental heat increases energy use and/or fixed costs at a given airflow. Supplemental heat reduces grain moisture content in the lower layers of the bin, but does not reduce moisture content in the top of the bin.

The controlled addition of supplemental heat (eg. electric heater on a humidistat, continuous fan operation) helps achieve the desired final moisture content and prevent rewetting during an extended period of damp, cold weather. Add heat only when the natural air cannot dry the grain (when relative humidity is above about 75%) to avoid overdrying.

If you want a lower final average moisture content by the end of fall:

- Increase airflow, or
- Add supplemental heat.

Between adding heat or increasing airflow, more air (shallower bins, larger fan) is usually the better choice. Additional airflow has more advantages (reliability, drying capacity) than increasing the drying air temperature.

Increased fan power:

- Speeds drying so that it is finished earlier in the fall when relative humidity is lower and results in a lower average final moisture content.
- Results in increased fan heat which increases temperature and reduces relative humidity of the drying air.
- May require excessive static pressure. Remember that doubling the airflow through a given depth of grain requires about 5 times as much power. Select large diameter, shallow bins to reduce static pressure at high airflows.
- Requires less energy than when heat is provided with an electric resistance heater. See Fig 3.

If you choose to add supplemental heat to an unstirred low temperature dryer, consider a solar collector. A solar collector can provide adequate supplemental heat for low temperature drying because:

- The longer drying period provides an extended period for collecting solar energy.
- Short periods of cloudy weather, and nights seldom cause problems because grain stores energy.
- High airflow requirements along with low temperature rises mean that simple, relatively inexpensive collectors can be used.

Pick a collector that heats drying air temperature an average of 2 F to 3 F over a 24-hour period. Design the collector, ducting, and transition to minimize additional static pressure. For more information, see the section on collector sizing.

Note that the additional static pressure from the collector, ducting, and transition can reduce airflow 10% to 15%. Select a fan that delivers the minimum recommended airflow despite the increased static pressure. Also, increased electrical demand and costs of the fan reduce potential benefits from the collector. And, keep in mind that solar heat is not a controlled heat source. It is not available on damp, cloudy days when it is needed. It is useful for reaching a lower average final moisture content if that is what you want. Providing heat with a solar collector reduces the amount of purchased energy compared to supplying heat with electricty.

Stirring and Low Temperature Drying

Although a stirring machine is not necessary in a properly designed and managed low temperature drying bin, it can provide some management advantages when drying conditions are unusually difficult. In a low temperature dryer a stirring machine:

- **Reduces overdrying.** Stirring mixes wet and dry grain and reduces moisture differences top to bottom. You can stop drying when the average moisture content is at the desired level instead of waiting for a top layer to dry. If natural air in your climate consistently dries below 15.5%, consider a stirring machine. Balance the cost of the stirrer against the cost of overdrying. Estimate the cost of overdrying at 2% of the market price of the corn/point of moisture below 15.5%/bushel. That is, if corn is dried to 13.5% and the market price is \$2.50 then, 2% x 2 points x \$2.50 = 10¢/bu. If supplemental heat causes overdrying, turn it off before deciding to buy a stirrer.
- **Increases airflow.** Stirring loosens grain which increases airflow. Airflow may be increased as much as 30% if a slinger-type distributor is used. Increased airflow decreases drying time and improves reliability of a low temperature dryer.
- Breaks up pockets of slow-drying grain.
- Eliminates the drying front. Grain does not dry in layers so there is a gradual moisture reduction in all of the grain and less chance of spoilage in the top.
- **Increases costs.** The total yearly cost of a stirrer (fixed and variable) is about 10¢/bu. This is between 25% and 35% of the yearly cost of a bin without the stirring machine. (Cost based on a 10,000 bu bin at \$13,000 construction cost without a stirrer, 10% interest rate, and a \$2,500 stirrer depreciated over 7 years.)
- Occupies about 2' of bin space. Install an extra ring to avoid loosing storage capacity.
- May be less reliable than other components of a low temperature dryer because of its complexity.

If you install a stirring machine in a low temperature drying bin, **continue to follow recommended procedures for low temperature drying, such as harvest moisture content and airflow rate.** For management suggestions, see Heated Air Stir-drying, below.

USING SOLAR HEAT FOR GRAIN DRYING

Heated Air Stir-drying

If you have a low temperature bin dryer with a stirrer, you can use solar heat to reduce purchased energy. In stirred bins, heat speeds drying and reduces the number of hours the fan runs. Use a collector that supplies a 24-hr average temperature rise of up to 10 F. More than 10 F provides little additional drying ability so fan time is not reduced much compared to the size and cost of the collector.

The machine shed roof and sidewall collector illustrated (see Collector Plans) can produce about 2,000,000 Btu/day in the fall in Lincoln, NE. A high temperature dryer might use 50,000,000 Btu/day to dry 10 points of moisture from 3,000 bu/day. The collector could replace about 4% of the purchased energy, or about 24 gal/day of LP.

If you have a high speed bin dryer with a stirrer, reduce gas consumption by preheating the air that goes to the burner with a solar collector. The high speed bin dryer can also be managed as a low temperature stirred bin when:

- Low temperatures are sufficient for drying.
- Moisture content is low enough that spoilage is not a major concern.
- Gas is not available.

Managing Bins with Stirrers

Manage bins with stirring devices carefully whether heat is added or not:

- Stir according to the amount of heat added. If more than 10 F is added, stir continuously. Continuous stirring in low temperature bins, however, can reduce airflow if fine material settles to the bottom. When less than 10 F is added, a complete stir once a week is sufficient, and reduces the chance of overstirring. Ask the manufacturer of the machine how long it takes for one complete stir.
- Intermittent stirring of low temperature dryers can cause problems when starting a stirrer in very wet corn, or in deep bins of drying corn. Pipe wrenches and/or special bracing may be required to start the machine without damaging the supporting framework.
- Some stirring devices do not work well in corn wetter than 25%. Some are prone to channeling—the down augers cut slots through the wet grain and follow these slots instead of mixing all of the grain.

High Temperature Drying

Preheating inlet air to high temperature dryers (any type) reduces the amount of fuel needed for drying. 83,700 BTUs of solar energy replaces one gallon of LP. Because of the high temperatures used, there is no limit on collector surface area besides cost and available space. Any heat from the collector reduces use of fossil fuels.

Desiccant System

If you have a solar collector that can provide heated air to a grain bin, you can use the desiccant system to store energy from summer into fall as the drying potential of overdried grain. (A desiccant is a material that can absorb moisture from, or dry, another material.) With this system, part of your fall corn drying is done before harvest.

During summer, overdry corn held over from the previous year's harvest down to 8%-10% with air heated by a solar collector. At harvest, remove part of the overdried corn from the desiccant bin and blend it with wet corn to produce a mixture with an average moisture content of 20%. Low temperature dry this mixture in a separate bin. Leave enough corn in the desiccant bin to produce another 20% moisture-content mixture when the bin is filled with wet corn. Solar stir dry this mixture to the desired moisture content.

Equipment Required

- A solar collector capable of producing a 25 F temperature rise at noon on sunny mid-summer days (about July 21). Two tilt angles are desirable: latitude - 10° for summer and latitude + 15° for fall. If your collector's tilt angle cannot be adjusted, set it equal to your latitude. Size the collector using insolation data from Table 22, appendix, and your collector's summer tilt angle.
  See Collector Sizing.
- Desiccant preparation bin(s) equipped with:
  Full drying floor.
  Stirring device.
  Fan that can deliver 1 cfm/bu when the bin is full and the collector is connected.
  Fan control: 24-hr timer wired in series with a humidistat that makes electrical contact when humidity falls.
- Corn held over from the previous year. Consider the corn as part of the dryer and the value of the corn as part of the dryer cost. The first year, the corn is an investment in the desiccant system. Each year after this, a similar amount is held over.

  You can calculate the amount of desiccant corn required to reduce the moisture content of an entire crop to 20%. Assume the desiccant corn will be at 10% moisture. (It may be lower.) Save up to that quantity of corn. See Example 10.
- Additional bin(s) equipped for low-temperature drying 20% corn.

Information developed by Dr. C. J. Bern, M. E. Anderson, and W. F. Wilcke, Iowa State University.

System Operation

Begin the desiccant preparation in early May:

1. Fill the desiccant bin with corn. (Empty the bin once a year to control insects and remove fines from the drying floor).
2. If your collector has an adjustable tilt angle, set it at the summer angle—your latitude minus 10°.
3. Set the humidistat at 50%. Set the timer so that electrical contact is made at 8 a.m. and broken at 6 p.m. Run the fan only during daylight hours when the ambient relative humidity is less than 50%. In mid-July, turn the humidistat down to 45%.
4. Turn on the power to the fan and leave it on until harvest. Remember, the fan runs only on days with low relative humidity.
5. Do not run the stirring device during desiccant preparation.

At harvest:

1. Run the stirring device for one complete stirring of the desiccant corn. (See the manufacturer's literature for how long this takes and how to start the stirrer in a full bin.)
2. Measure the moisture content of the desiccant corn. Most electrical moisture meters do not work well at moisture contents below 10%. In tests at Iowa State University the actual moisture content of corn was from 8%-11% when the meter read 11%. Because the meter usually reads high in this moisture range, the actual moisture content of the desiccant/wet-corn mixture may be less than the calculated 20%. The Dexter modified oil-distillation method works at all moisture levels. See pamphlet Pm-275, available from Iowa State University Cooperative Extension Service.
3. Measure the moisture content of the wet corn.
4. Calculate the quantity of desiccant corn to be left in the bin to produce a 20% moisture-content mixture when the bin is filled with wet corn. See Example 10.
5. Calculate the quantity of wet corn that can be blended with the extra desiccant to produce more 20% corn. See Example 10.
6. Carefully blend the extra desiccant and wet corn.
    - Run desiccant corn into the dump pit or auger hopper as the wet corn is unloaded, or
    - Put both the wet and dry fractions into a bin with a stirring device; stir to blend the fractions.

    Use a grain spreader when filling a bin with blended corn. Wet and dry corn separate if the blend is dropped on a pile.
7. Low-temperature dry the blended corn.
8. Set the solar collector at the fall angle—your latitude plus 15°.
9. Disconnect the humidistat and timer so the drying fan on the desiccant bin can run continuously.
10. Fill the desiccant bin with wet corn and run the stirring device for one complete stirring.
11. Solar stir dry the corn in the desiccant bin to the desired final moisture content. See Heated Air Stir-drying.

When blending wet and desiccant corn, you must measure and calculate on a weight rather than volume basis. Therefore, Example 10 uses "dry-matter bushels." Each dry-matter bushel has 47.32 lb of bone-dry corn plus water—the amount of water varies with moisture content, Table 13. At 15.5%, a dry-matter bushel weighs 56 lb: 47.32 lb dry matter + 8.68 lb water = 56 lb.

A dry-matter bushel is not the same as a "volume bushel" (1.245 ft^3). One dry-matter bushel of wet corn is usually more than 1.245 ft^3 and of dry corn is usually less than 1.245 ft^3. So, a bin rated at 6000 bu (volume basis) may hold less wet corn, but more dry corn than the 6000 bu (dry matter basis). Besides moisture content, the volume of a dry-matter bushel in a bin depends on corn variety, weather during the growing season, bin filling method, whether a stirrer was used, etc. Because of these factors, there is really no typical volume for a dry-matter bushel.

The dry-matter bushel is not the same as the one common in commercial trade, either. The commercial bushel is 56 lb of corn—regardless of moisture content. For example, 200,000 lb of 30% corn is 200,000 lb/67.60 lb-bu = 2959 dry matter bushels (Table 13), but 200,000 lb/56 lb-bu = 3571 bu at the elevator.

Example 10: A farmer saved 3000 dry-matter bu of corn for a desiccant drying system. Average moisture content of the stirred desiccant at the end of the summer is 8%. New corn is coming in at 24%.

1. Find how much 8% corn produces a 3000-bu mixture of 20% corn in the desiccant bin.

Answer: It takes 2.5 bu of 24% corn for every bu of 8% corn for a 20% mixture, Table 12.

$$\text{Required bu desiccant} = \frac{\text{Blended bu}}{\text{Mixing ratio} + 1}$$

$$= \frac{3000\text{ bu}}{2.5 + 1} = \frac{3000\text{ bu}}{3.5} = \mathbf{857\ bu}$$

2. Find the weight of 8% corn removed from the desiccant bin.

Answer: 3000 bu - 857 bu kept in bin = 2143 bu
8% corn weighs 51.43 lb/bu (Table 13):
2143 bu x 51.43 lb/bu = **110,214 lb**

3. Find the weight of 24% corn needed to produce a 20% mixture in the desiccant bin.

Answer:
Bu wet corn = Bu desiccant x Mixing ratio = 857 bu x 2.5 = 2143 bu
24% corn weighs 62.26 lb/bu (Table 13):
2143 bu x 62.26 lb/bu = **133,423 lb**

4. Find the weight of 24% corn to produce a 20% mixture with the 8% corn removed from the desiccant bin.

Answer:
Bu wet corn = Bu desiccant x Mixing ratio = 2143 bu x 2.5 = 5358 bu
5358 bu x 62.26 lb/bu = **333,589 lb**

5. Find the total bushels of 24% corn "dried" to 20% by the 3000 bu of desiccant.

Answer:
Bu wet corn = Bu desiccant x Mixing ratio = 3000 bu x 2.5 = **7500 bu**

Table 12. Mixing ratios for wet and desiccant corn.

Bushels of wet corn mixed with each bushel of desiccant corn to get a 20% moisture-content mixture. 1 bu = 56 lb of 15½% corn; see Table 13 for wet bushel weights.

MC wet corn %	Moisture content, MC, of desiccant corn, percent										
	5	6	7	8	9	10	11	12	13	14	15
	Bu wet per bu dry corn, bu/bu										
21	12.5	11.8	11.0	10.3	9.5	8.8	8.0	7.2	6.4	5.5	4.6
22	6.1	5.8	5.4	5.1	4.7	4.3	3.9	3.5	3.1	2.7	2.3
23	4.1	3.8	3.6	3.4	3.1	2.9	2.6	2.3	2.1	1.8	1.5
24	3.0	2.8	2.7	2.5	2.3	2.1	1.9	1.7	1.5	1.3	1.1
25	2.4	2.2	2.1	2.0	1.8	1.7	1.5	1.4	1.2	1.1	0.9
26	2.0	1.8	1.7	1.6	1.5	1.4	1.3	1.1	1.0	0.9	0.7
27	1.7	1.6	1.5	1.4	1.3	1.2	1.1	1.0	0.8	0.7	0.6
28	1.4	1.3	1.3	1.2	1.1	1.0	0.9	0.8	0.7	0.6	0.5
29	1.3	1.2	1.1	1.0	1.0	0.9	0.8	0.7	0.6	0.6	0.5
30	1.1	1.0	1.0	0.9	0.9	0.8	0.7	0.6	0.6	0.5	0.4

Advantages of the desiccant system:

- The solar collector is used during the summer when it would otherwise be idle. This increases the total hours of use and total amount of energy produced by the collector.
- You can reduce the initial moisture content of at least part of your harvest. Lower moisture content corn can be dried with lower airflow—which means smaller fans.
- Research at Iowa State University has shown that both the electrical power demand (connected kilowatts) and total electrical energy consumption (kilowatt hours) are lower for the desiccant system than conventional low-temperature drying systems.

Disadvantages:

- High equipment requirements, including the desiccant corn, which could have been sold, and the additional space to store the desiccant corn.
- Overdrying and then rewetting corn kernels may lead to increased breakage susceptibility. Damage tests have been run on lab samples, but not on samples from the field tests.
- Difficulty in obtaining the moisture contents of the desiccant and the blended corn. Most electrical moisture meters are not accurate for either very dry corn or blended corn. They respond more to the wet fraction in recently blended corn and give readings higher than the calculated average moisture content.

We do not now recommend blending corn to 15½% for immediate sale or storage. For one thing, the meter at the elevator indicates moisture greater than 15½% and the purchase price will probably be docked. For another, without drying air the wet corn will probably spoil before moisture equalizes between the wet and dry kernels. More research is needed on managing corn blended to 15½%.

Table 13. Wet weights of corn.

1 bu = 47.32 lb dry matter, and = 56 lb at 15½%.

Moisture content % wet basis	Wet weight lb/bu	Weight of water in a bushel lb/bu
5	49.81	2.49
6	50.34	3.02
7	50.88	3.56
8	51.43	4.11
9	52.00	4.68
10	52.58	5.26
11	53.17	5.85
12	53.77	6.45
13	54.39	7.07
14	55.02	7.70
15	55.67	8.35
15.5	56.00	8.68
16	56.33	9.01
17	57.01	9.69
18	57.70	10.39
19	58.42	11.10
20	59.15	11.83
21	59.90	12.58
22	60.67	13.35
23	61.45	14.13
24	62.26	14.94
25	63.09	15.77
26	63.95	16.63
27	64.82	17.50
28	65.72	18.40
29	66.65	19.33
30	67.60	20.28

SOLAR ENERGY FUNDAMENTALS

Solar energy comes from thermonuclear reactions in the core of the sun. The energy is mostly shortwave radiation emitted into space in all directions. When the radiation strikes a material, it reflects off, passes through, or is absorbed. The absorbed fraction usually causes the material to heat. With the proper combination of materials, you can build a solar collector to collect this heat.

Solar energy is nonpolluting and inexhaustible. The energy itself is free, but the equipment required to collect and use it is not. Solar equipment costs, relative to fossil fuel (coal, gas, and oil) costs, have slowed solar development. But as fossil fuel supplies dwindle and fuel costs continue to rise, solar energy collection should become more economically feasible for many applications. Solar energy can reduce our dependence on fossil fuels, but its availability seems too variable and too limited to completely replace fossil fuels.

This discussion of Solar Energy Fundamentals gives basic information on solar energy and on collecting and using it as heat energy. Agricultural applications—especially those using heated air—are emphasized. Knowledge of solar energy fundamentals will help you:

- Determine how much solar energy is available in your area.
- Select the best type of commercial or home-built collector for your situation.
- Modify a solar collector plan or design a collector to meet your needs.
- Calculate the size of solar collector you need.
- Decide whether you should use solar energy at all.

Available Solar Energy

The intensity of solar energy, or solar radiation, decreases with greater distance from the sun. The sun is not at the center of the earth's orbit, so the earth's distance from the sun varies during the year and so does the intensity of the radiation reaching the earth. About 428 Btu/hr-ft^2, the solar constant, reaches a surface facing the sun, and just outside the earth's atmosphere, 24 hr/day. But only a fraction of this energy is available to solar collectors on the earth's surface. The energy available on a collector surface depends on the time of day, the time of year, the weather, the latitude of the collector site, and the collector's tilt angle.

Day-Night Cycle

Because of the earth's rotation on its axis, solar collectors on the earth are in darkness part of each 24 hrs. For example, Fig 17 shows the energy available on a sun-following surface (one that is always pointed directly at the sun) on several clear days at 40° north latitude. The energy intensity increases from 0 just before dawn to some maximum value at noon and then decreases to 0 again at dusk. The curves in Fig 17 are for: Dec. 21, the first day of winter and the shortest day of the year (winter solstice); June 21, the first day of summer and the longest day of the year (summer solstice); and Mar. 21, the first day of spring and the day when the hours of darkness equal the hours of daylight (spring equinox). Sept. 21, the first day of fall (fall equinox), is similar to Mar. 21.

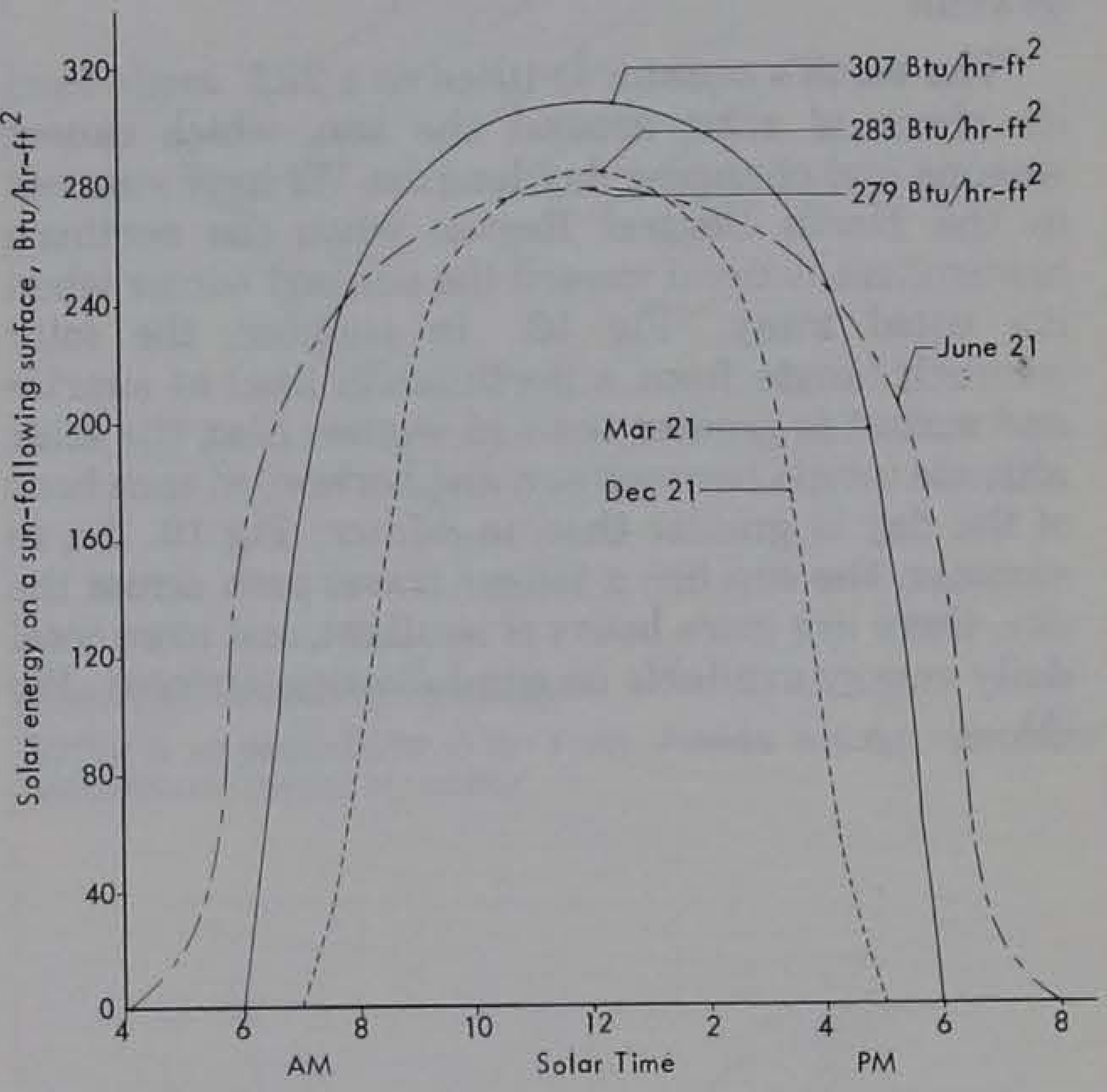


Fig 17. Hourly clear day radiation.
Sun-following surface. 40° north latitude.

The intensity of the noon, clear-day solar radiation on sun-following surfaces at 40° north latitude is greater on Mar., Sept., and Dec. 21 than it is on June 21—about 307 Btu/hr-ft^2 and 283 Btu/hr-ft^2 vs 279 Btu/hr-ft^2. See Fig 17. The intensity is less in June because the earth is farther from the sun. Fig 18.

Solar time (used in Fig 17) is not the same as local time. At solar noon the sun is at its highest point in the sky for the day. Solar noon varies from local clock noon depending on the time of year, where you live in the time zone, and whether Daylight Savings Time is in effect.

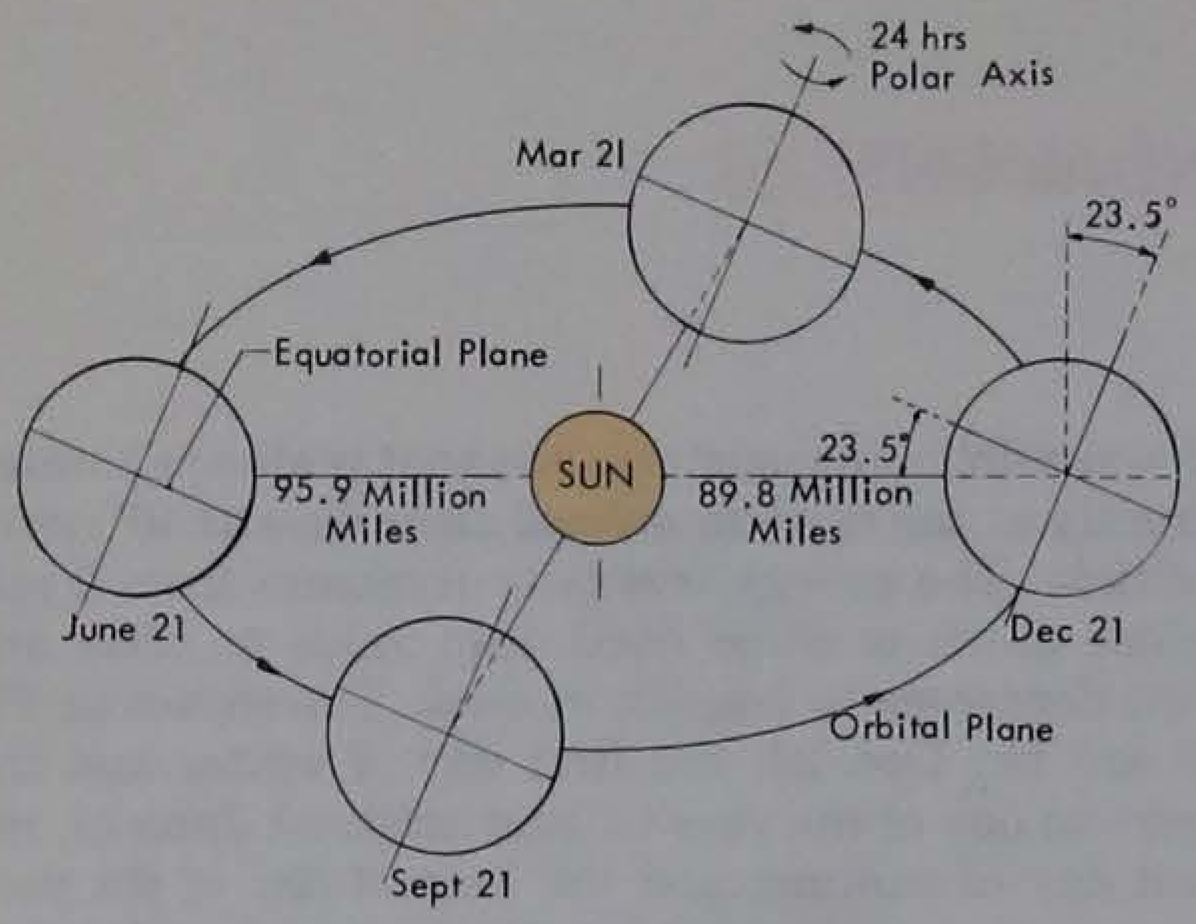


Fig 18. Earth's motion around the sun.
Solar year is one revolution of 364¼ days.

Season

The earth's equator is tilted at a 23.5° angle from its plane of orbit around the sun, which causes seasons and changing day lengths. We have summer in the North Central Region when the northern hemisphere is tilted toward the sun and winter when it's tilted away. Fig 18. In summer, the solar azimuth (angle from a north-south line) at sunrise and sunset is greater than in winter. Also, the solar altitude (angle between sun and horizon) at each hour of the day is greater than in winter. Fig 19. So, in summer, the sun has a longer travel path across the sky, there are more hours of sunlight, and more total daily energy available on sun-following surfaces. Fig 20.

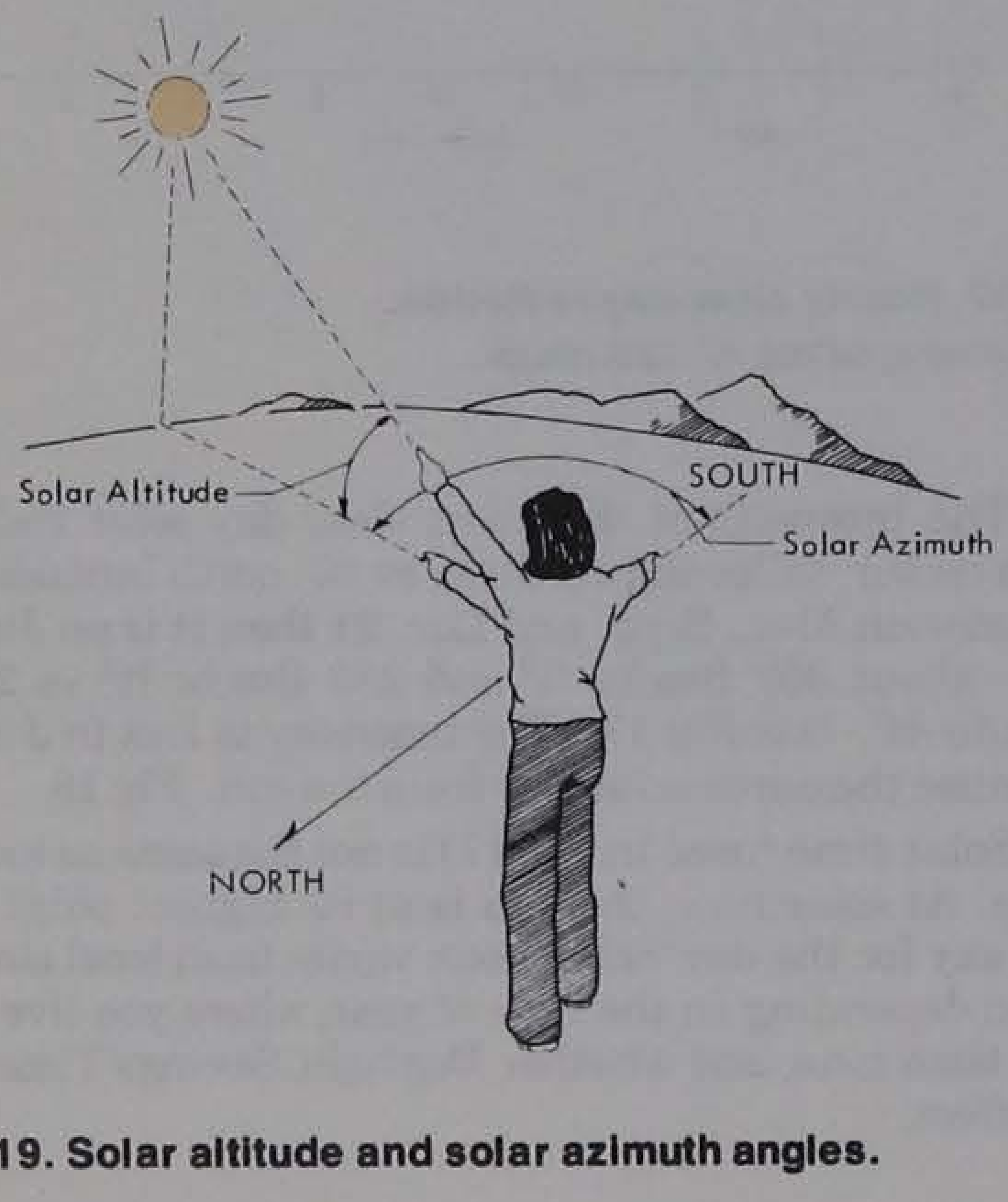


Fig 19. Solar altitude and solar azimuth angles.

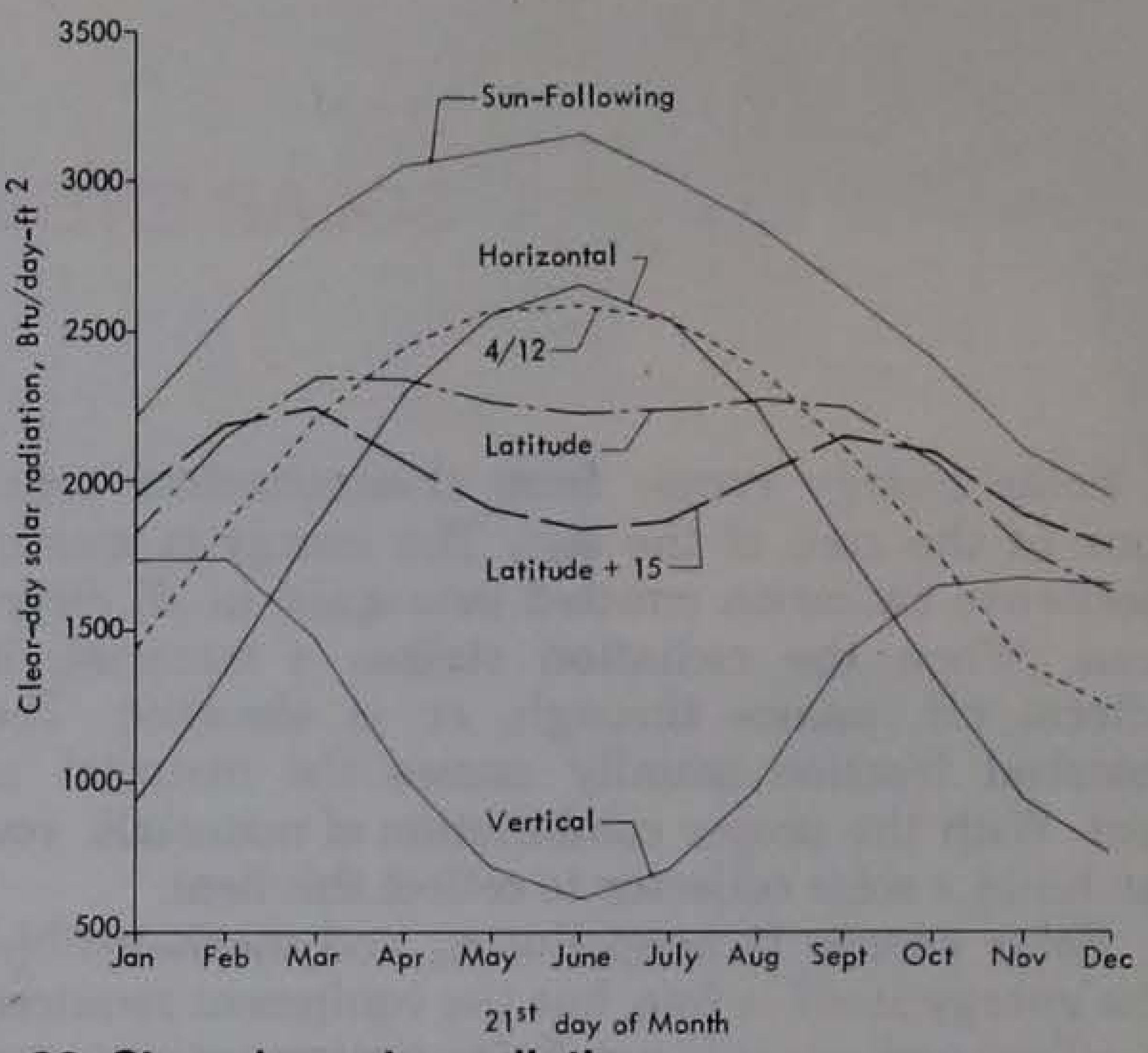


Fig 20. Clear day solar radiation.
South-facing surface. 40° north latitude. Curve labels are tilt angles from horizontal.

Atmospheric Effects

In Fig 17, the maximum energy available on clear days on sun-following surfaces is 307 Btu/hr-ft^2—less than three-fourths the amount available outside the earth's atmosphere. Part of the 428 Btu/hr-ft^2 arriving from the sun is reflected back into outer space at the top of the atmosphere, Fig 21. Some is absorbed by the ozone layer, water vapor, carbon dioxide, and other compounds making up the atmosphere. Another portion of solar radiation is scattered by dust particles or water vapor and is not available on sun-following surfaces.

Early in the morning and late in the afternoon when the sun is low in the sky, the sun's rays travel through much more of the atmosphere than at midday. More energy is absorbed and scattered in the atmosphere and less reaches the earth's surface. Also, the sun's rays strike the earth's atmosphere at a much flatter angle and a greater fraction is reflected. Thus, on clear days the maximum amount of solar energy is available at midday, Fig 17, and the maximum temperature rise in a solar collector occurs near solar noon.

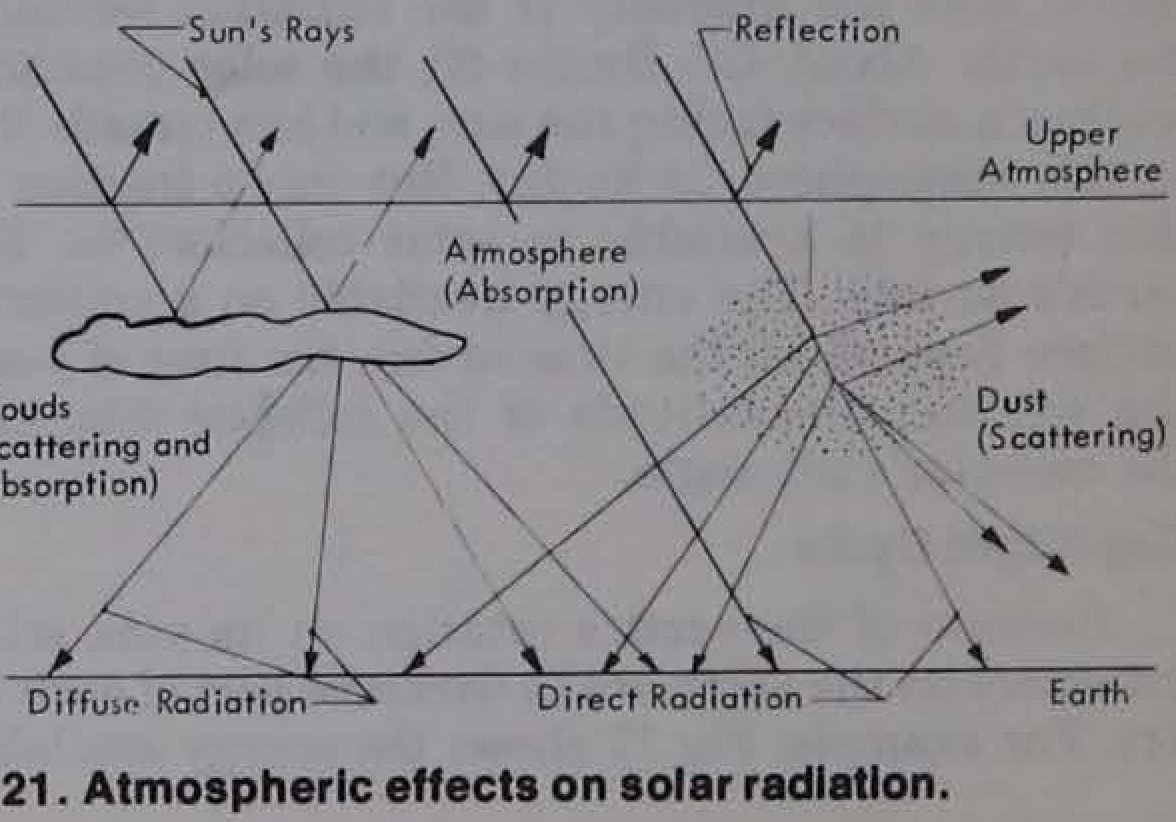


Fig 21. Atmospheric effects on solar radiation.

Solar radiation that passes directly from the sun to the earth's surface without deflection is called direct or beam radiation. The fraction that has been scattered is diffuse radiation. On clear days, about 85% of solar radiation is direct and 15% is diffuse. The quantity of solar energy available on clear days is mainly a function of latitude (distance from the equator) and season and is fairly predictable. Figs 17 and 20, and Table 22, appendix.

When clouds are present, much more solar radiation is absorbed and scattered. On completely overcast days, all solar radiation is diffuse and much less solar energy is available. Cloud cover at any location varies from hour to hour, day to day, and year to year and is unpredictable. Because cloud cover cannot be predicted, the amount of solar energy available cannot be accurately predicted. The best we can do is average the solar radiation received at a location over a number of years and assume that, on the average, the same amount will be received in the future. Table 23, appendix.

Weather and atmospheric conditions are very localized, so even two sites at approximately the same latitude can have very different radiation. For example, on a south-facing vertical surface in Lincoln, NE you expect an average of 1346 Btu/day-ft^2 in December (Table 23i, appendix). On a similar surface in Columbus, OH (about the same latitude), you expect only 686 Btu/day-ft^2, (Table 23d, appendix). Columbus is more industrialized than Lincoln and is in a more humid region, so the air over Columbus contains more smog, water vapor, and clouds, and less solar energy reaches the collector.

Surface Orientation

A sun-following surface, or one that is always pointing directly at the sun, receives the most energy per day, Fig 20. This surface has the greatest possible intercept area and because the angle of incidence is 0°, has a minimum of reflection, Fig 22. The angle of incidence or incident angle is the angle between the sun's direct rays and a line normal (at right angles) to the surface, Fig 23.

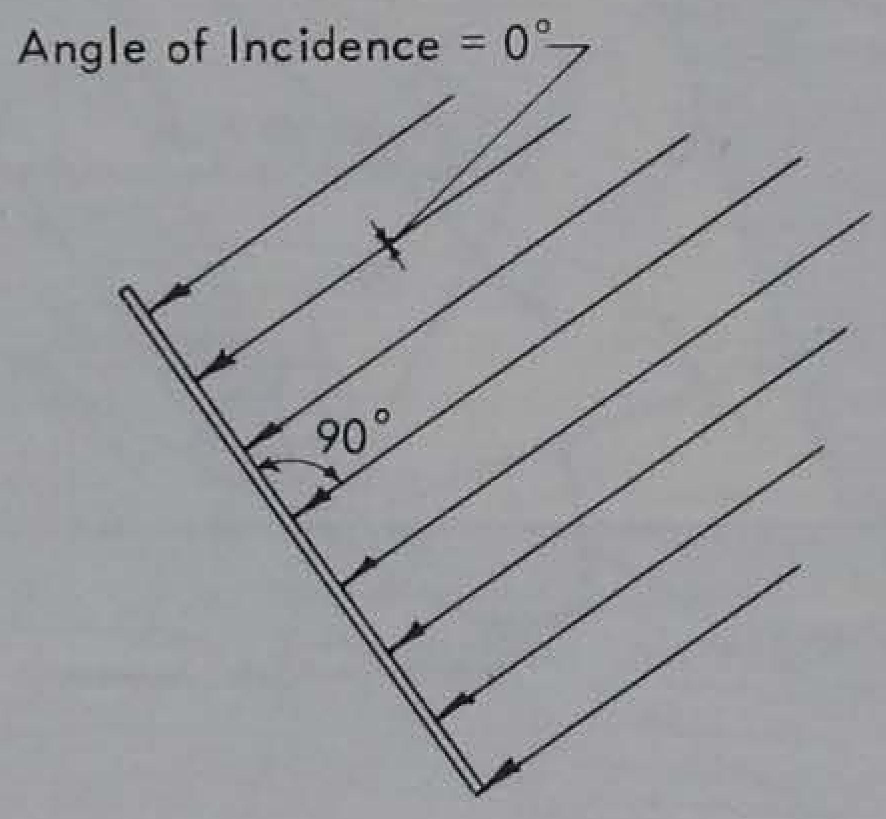
A sun-following surface follows or tracks the sun's movement across the sky. It must pivot both horizontally and vertically to follow the sun's changes in altitude and azimuth. Tracking requires a device to sense the sun's position, a mechanism to move the collector, and a fairly complex support structure. Tracking usually increases costs and maintenance requirements.

A somewhat simpler collector tracks the sun in only one direction—either altitude or azimuth. A fixed collector is even simpler and cheaper but does not track the sun at all. Less solar energy is available to a fixed collector than a tracking one, but the cost is usually enough lower to pay for extra collector area to make up the difference.

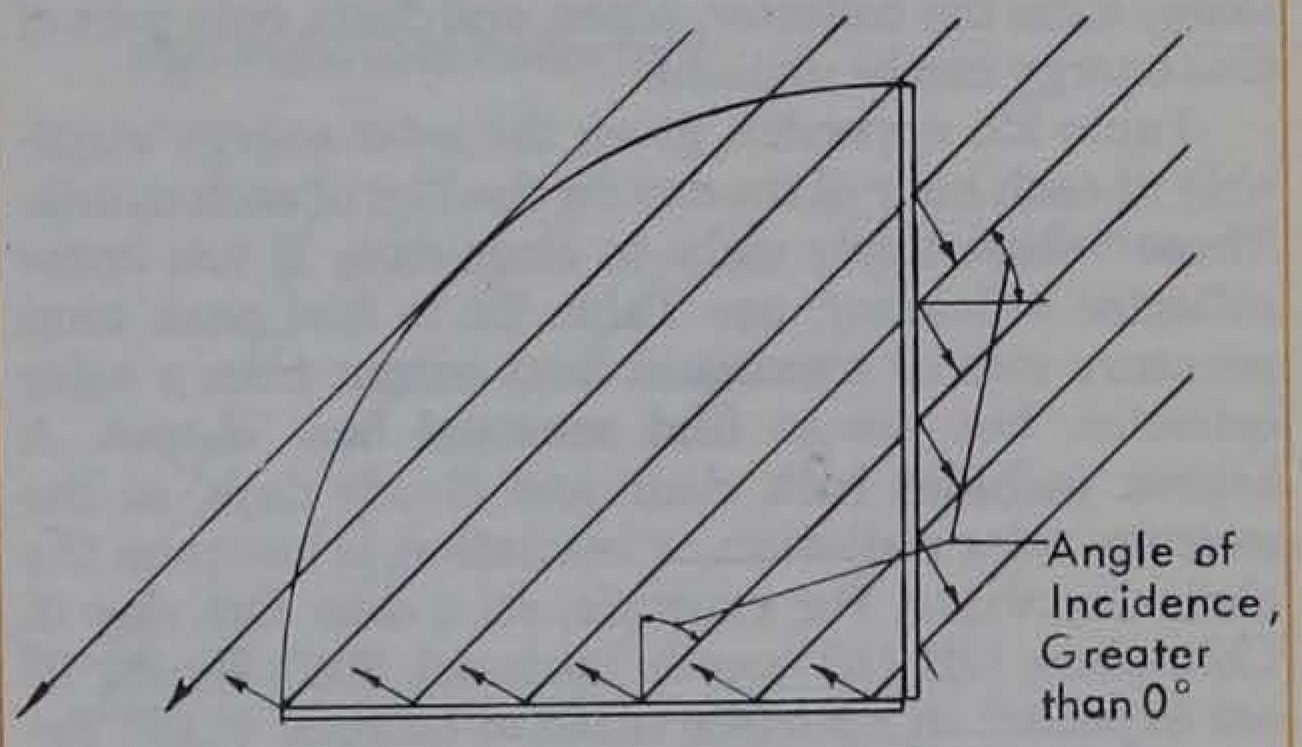
In the northern hemisphere, fixed solar collectors generally receive the most energy per day if they face due south. But, deviations up to 15° from due south make little difference in the total energy received. Under some circumstances, southeast or southwest settings may be more desirable. For example: an obstruction blocks the morning or afternoon sun, or you want to collect more energy in the morning or afternoon.

Set the tilt angle of a fixed collector so the solar angle of incidence is near 0° at solar noon. The collector will be like a sun-following collector at midday, but in the morning and afternoon, when the solar angle of incidence is high, much solar radiation will reflect off the collector.

Because the sun's altitude varies with the latitude and time of the year, the best tilt angle for a fixed solar collector depends on when and where it will be used. The curves in Fig 20 show that at 40° north latitude a vertical south-facing surface (such as a building wall) receives much energy October through



22a. Sun-following surface.
Surface is set perpendicular to sun's rays. Provides maximum interception and minimum reflection of radiation.



22b. Other surfaces.
Surfaces are not perpendicular to sun's rays. Less than maximum radiation is intercepted and more radiation is reflected.

Fig 22. Radiation on a sun-following surface.

February when the solar altitude is low, but relatively little the rest of the year. A horizontal surface receives the most energy (of the fixed surfaces shown) during the summer when the solar altitude is high, but the least during the winter months. The other tilt angles shown are equal to the latitude (40° from horizontal in this case), latitude + 15° (55°), and a 4/12 slope (18.4°).

Surfaces with latitude + 15° tilt angle receive more energy than the other fixed surfaces shown from Oct. through Feb. Therefore, for maximum energy collection in the North Central Region, set the tilt angle of grain drying and space heating collectors at your latitude + 15°. Collectors used year around are generally set at a tilt angle equal to the latitude.

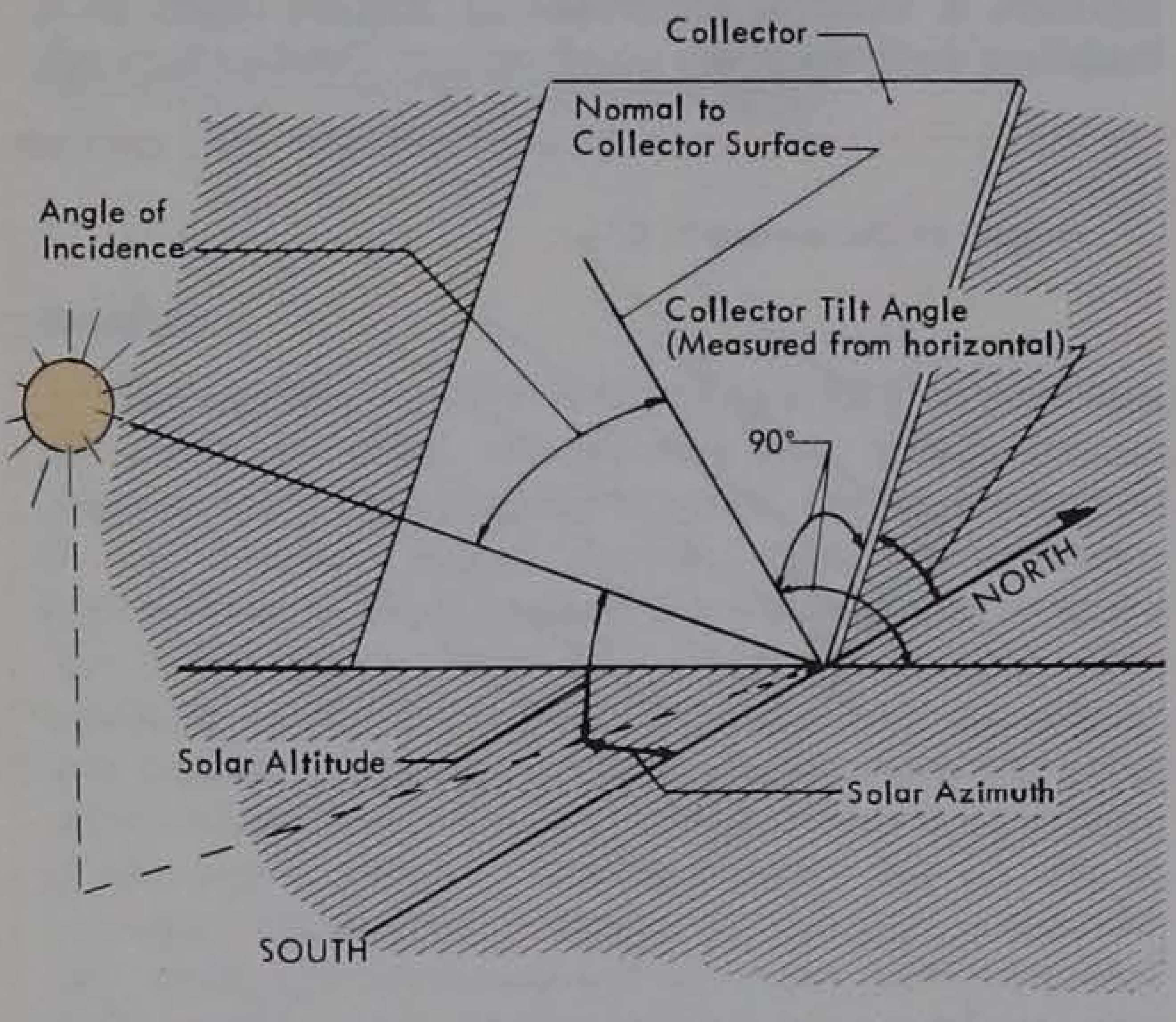


Fig 23. Solar angle of incidence on south-facing surface.

Explanation of Solar Radiation Tables

Tables showing the solar energy available in the North Central Region are in the appendix. The tables give energy **available** on a collector surface. Due to losses from the collector, pipes, and ducts, only part of this energy can be utilized.

Table 22, appendix, gives the solar energy available at each hour of the day on the 21st of each month. These values apply **only** to clear days. If you know collector efficiency, use Table 22 to find peak temperature rise or maximum heat output from a solar collector, but not to find seasonal heat output. A season includes both clear and cloudy days, so the average solar radiation, or insolation, is less than the clear-day value. For example, on a clear Oct. day in Columbus, OH (40° north latitude), 2087 Btu/hr-ft^2 are expected on a surface tilted at latitude + 15°, Table 22c. The average insolation on the same surface in Oct. is only 1170 Btu/hr-ft^2, Table 23d, appendix.

Clear-day insolation values include direct and diffuse radiation, but not radiation reflected off the ground or other surrounding surfaces. The values are for average clear days. On exceptionally clear, dry days, the insolation actually received could be up to 15% greater. Find your latitude on the map in the appendix and use the table for the latitude closest to yours. Fig 41.

Table 23 gives the average daily total solar energy available on various surfaces. The energy includes direct and diffuse radiation and radiation reflected off the ground. (Snow cover was considered in the calculations—snow reflects more solar radiation than grass or bare soil.) The values are monthly averages of years of actual solar data at 13 weather stations in the North Central Region. The graphs and tables are for the same data.

If you know your collector efficiency, use data from the station nearest to you in Table 23 to calculate the average energy or temperature rise produced by your collector in a season. In unusually sunny years, the collector's temperature rise or heat output will exceed the calculated value. In cloudy years, collector output will fall short of your calculated value.

Even though surfaces tilted at latitude + 15° during the grain drying and heating season receive more solar energy, it is often cheaper or more convenient to mount solar collectors on other surfaces. Consider south-facing sidewalls and roofs. Use Tables 22 and 23 for the tilt angle closest to the tilt angle of your collector.

Collector Shading

A solar collector's effectiveness is reduced if it is shaded by buildings, bins, trees, or other collectors. Separate the collector far enough from obstructions south of it to prevent shading. Calculate the necessary separation distance with the solar angle factor, Table 14. Daily total insolation values in the appendix do not apply to a collector shaded part of the day.

Example 11: Find the separation required to prevent shading by a 20' high east-west building during the heating season at 40° north latitude.

Answer: Maximum separation is needed on Dec. 21 when the sun is lowest in the sky. From Table 14, the solar angle factor, d/h = 1.96.
Separation distance (ft)
= d/h x Obstruction height (ft)
= 1.96 x 20 ft = **39 ft**

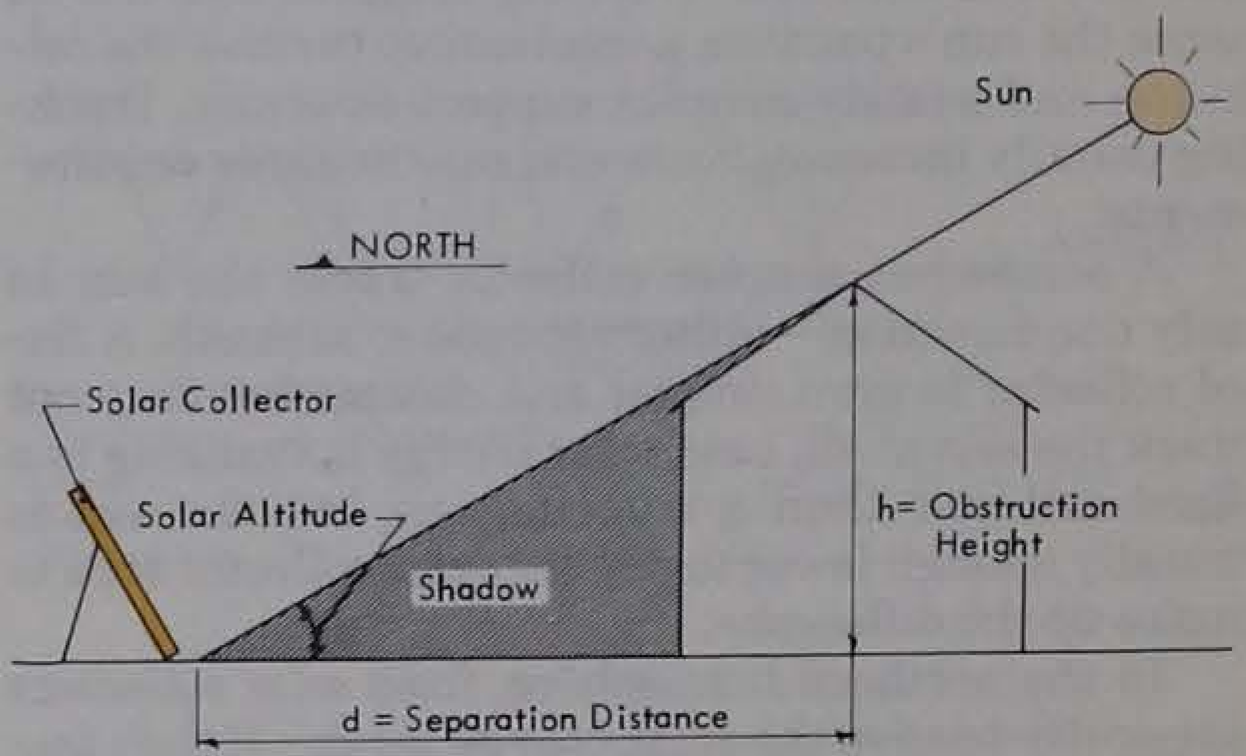


Fig 24. Separation distance to prevent shading.

Put the collector at least 39' north of the building to prevent shading at noon. Some shading will occur in the morning and afternoon unless the separation distance is greater than 39 ft.

Shading can be an advantage if the collector is not used during the summer. Shading prevents undesirable heating and protects the collector from damaging high temperatures.

Example 12: Find the overhang to shade an 8' vertical collector May through July at 40° north latitude.

Answer: Find the appropriate solar angle factor, Table 14. For this period, the longest overhang would be required in May and July. d/h = 0.36.
Overhang length (ft)
= d/h x Collector height (ft)
= 0.36 x 8 ft = **2.88 ft**

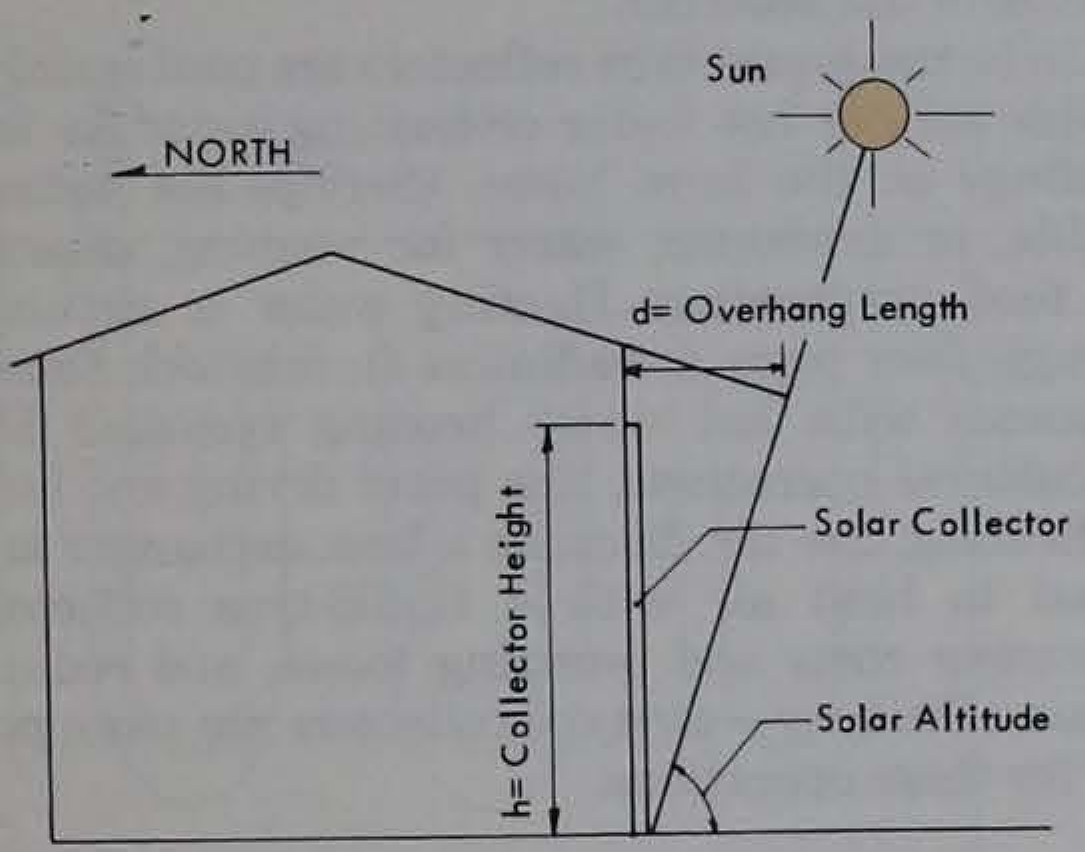


Fig 25. Overhang length to shade collector.

The collector is completely shaded at noon May 21 through July 21, but only partially shaded in the morning and afternoon. If more shading is desired, make the overhang longer. A 2.88' overhang partially shades the collector during portions of the heating season. If this is undesirable, make the overhang shorter than 2.88', or remove it during the heating season.

Table 14. Solar angle factors.
d/h = 1/tan B, where B = solar altitude at solar noon.

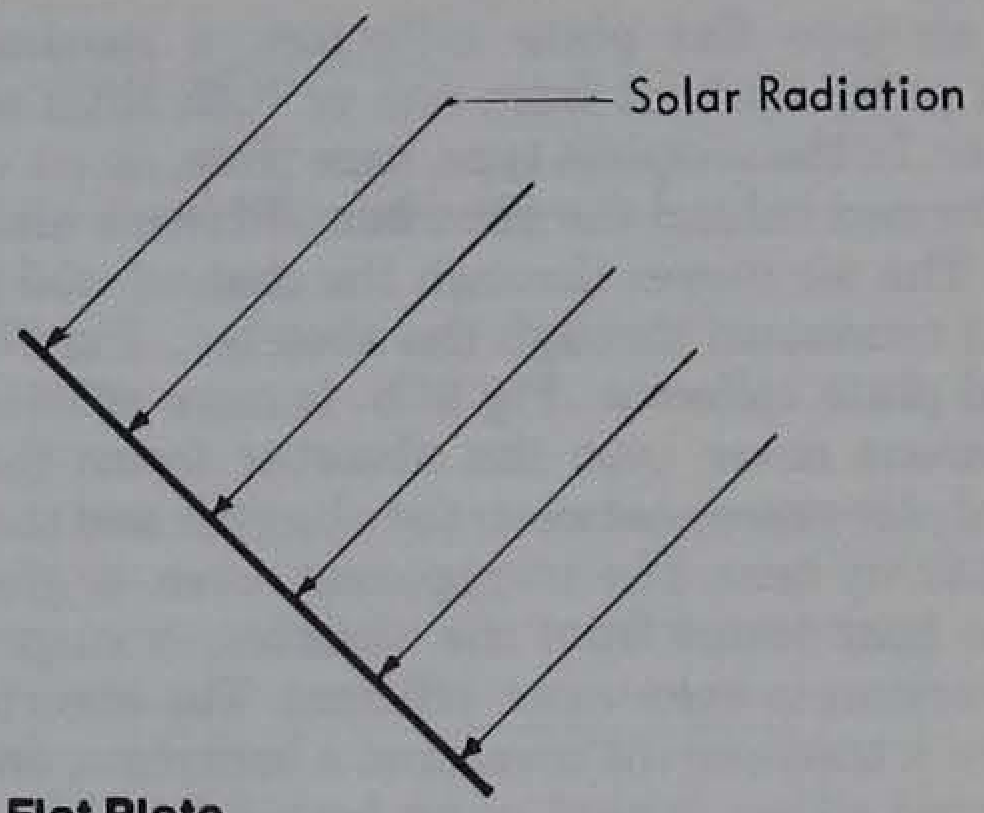
Date	36	38	40	42	44	46	48
			Latitude, degrees north				
	- - - - Solar angle factor, d/h - - - -						
Jan 21	1.48	1.60	1.73	1.88	2.05	2.25	2.48
Feb 21	1.07	1.15	1.23	1.33	1.43	1.54	1.66
Mar 21	0.73	0.78	0.84	0.90	0.97	1.04	1.11
Apr 21	0.45	0.49	0.53	0.58	0.62	0.67	0.73
May 21	0.29	0.32	0.36	0.40	0.45	0.49	0.53
Jun 21	0.23	0.27	0.31	0.34	0.38	0.42	0.47
Jul 21	0.29	0.32	0.36	0.40	0.45	0.49	0.53
Aug 21	0.45	0.49	0.53	0.58	0.62	0.67	0.73
Sep 21	0.73	0.78	0.84	0.90	0.97	1.04	1.11
Oct 21	1.07	1.15	1.23	1.33	1.43	1.54	1.66
Nov 21	1.48	1.60	1.73	1.88	2.05	2.25	2.48
Dec 21	1.66	1.80	1.96	2.14	2.36	2.61	2.90

Collector Types

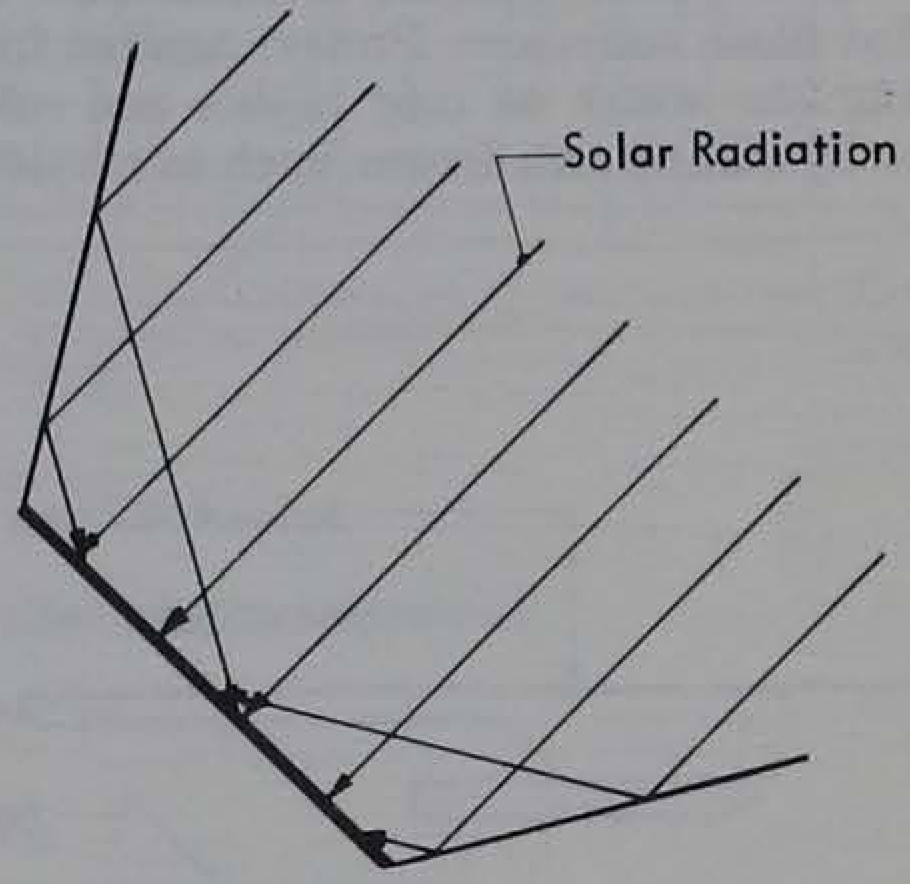
The purpose of the solar collectors discussed in this handbook is to:

- Intercept radiation from the sun;
- Convert this solar energy into thermal (heat) energy;
- Transfer the heat energy to a fluid (air or liquid) that carries it to the point of use or heat storage.

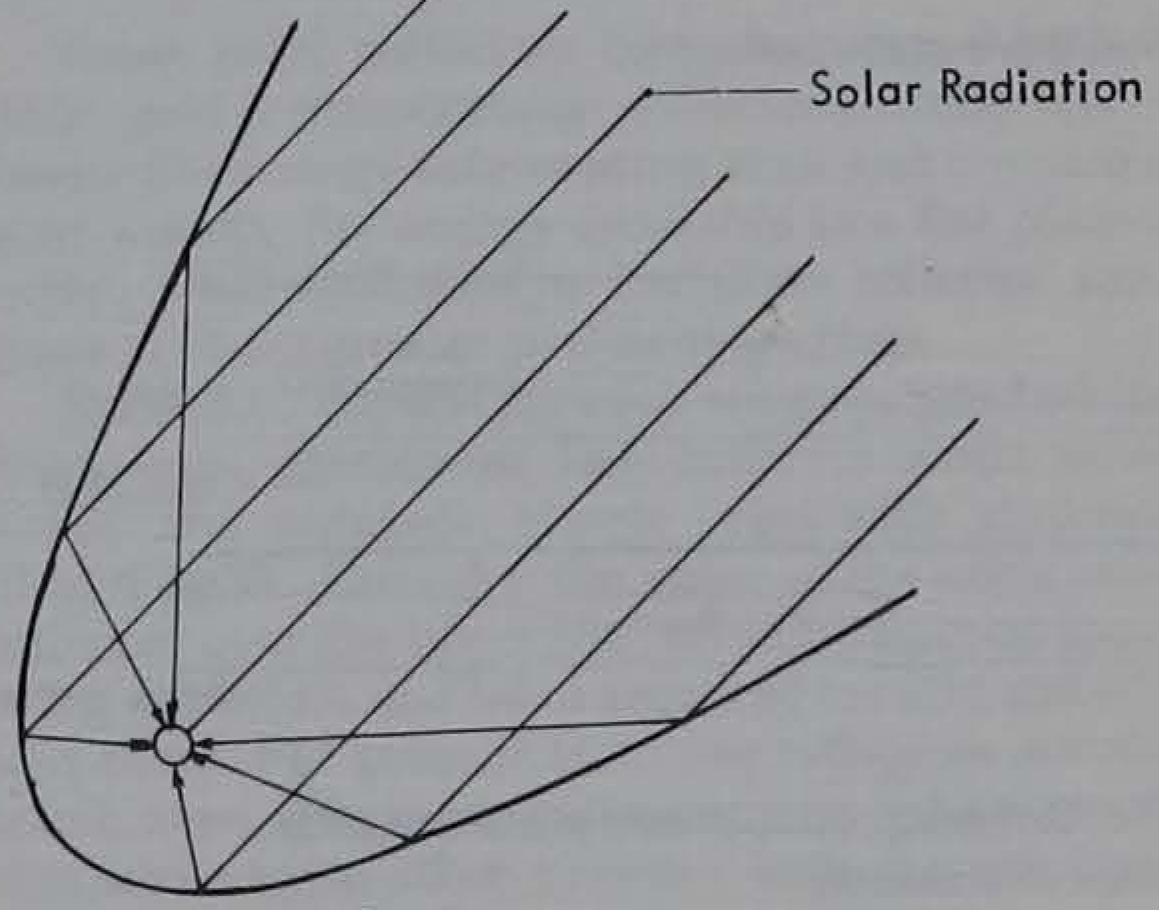
Basic types of solar collectors are flat plate and concentrating. A flat plate collector with reflectors has characteristics of both. Fig 26.



Flat Plate



Flat Plate with Reflectors



Concentrating

Fig 26. Basic types of solar collectors.

Flat Plate Collectors

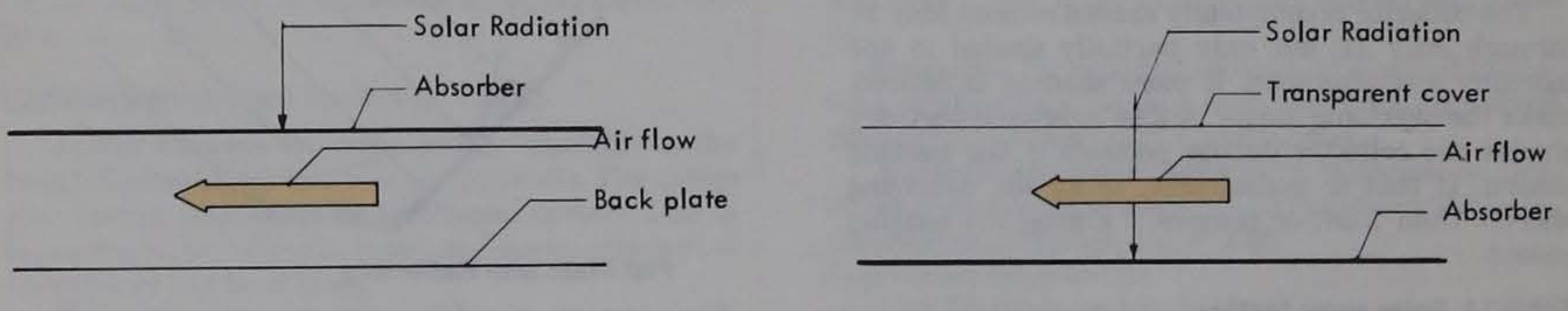
An important part of a flat plate collector is the absorber, or absorbing surface. The absorber is essentially flat, but can be perforated, corrugated, finned, or crimped. It absorbs solar energy, heats up, and then transfers the heat to the fluid moving over or through it. The area of the absorber in a flat plate collector about equals the energy intercepting area. Most flat plate collectors are fixed. They collect both direct and diffuse radiation, so they may produce small amounts of heat even on overcast days when all solar radiation is diffuse.

In air-type flat plate collectors, a moving air stream picks up heat from one or both sides of the absorber. In the simplest type, bare plate, an air channel is formed behind the absorber with back and side plates. The air moves through the channel and picks up heat conducted through the absorber. Fig 27a. A covered plate collector ,Fig 27b, is more efficient. A transparent cover over the absorber forms the air channel. Air passes between the absorber and the cover to pick up heat. The transparent cover, or glazing, reduces heat losses from the absorber. A suspended plate version is even more efficient. The absorber is between a transparent cover and a backplate, and air is directed either behind or on both sides of it. Figs 27c and 27d.

Water is often the heat transfer fluid in liquid-type flat plate collectors. Protect against freezing by draining the water on cold nights and cold, cloudy days or by adding anti-freeze, such as ethylene glycol. On sunny days when the collector is not in use and the liquid is stagnant (not moving), temperatures inside the collector can exceed 300 F. Protect against damage from boiling liquid by draining the collector or providing a pressure relief valve. In addition to boiling and freezing problems, liquid-type systems are prone to corrosion, scale build-up, and fluid leakage.

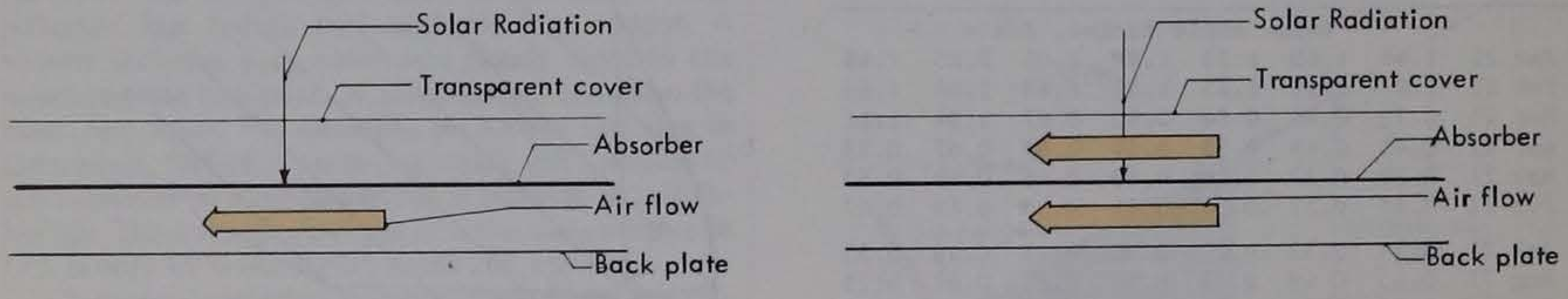
In most liquid-type flat plate collectors, the liquid is in tubes soldered to the absorber, Fig 28 . The tubes are in a serpentine pattern ,Fig 28c, or a parallel pattern with headers or manifolds on each end ,Fig 28d . Covered plate liquid-type collectors are much more common than bare plate ones. In some liquid-type collectors, cool liquid enters at the top of a sloped absorber and trickles down open channels in the absorber surface. The heated liquid is collected at the base of the absorber.

On farms, liquid-type collectors are used mainly to provide service hot water or heating water for farm buildings or the farm home. (Service hot water is potable, or drinkable, water for washing, cleaning, and food preparation. Heating water is circulated through floor pipes or radiators in livestock housing or homes with hot water heating systems.) Most agricultural operations, like grain drying and building heating, use air. Because a heat exchanger is required to heat air with a liquid-type collector—increasing costs and pumping losses, and reducing system efficiency—air-type collectors are more practical for these operations.



27a. Bare plate collector.

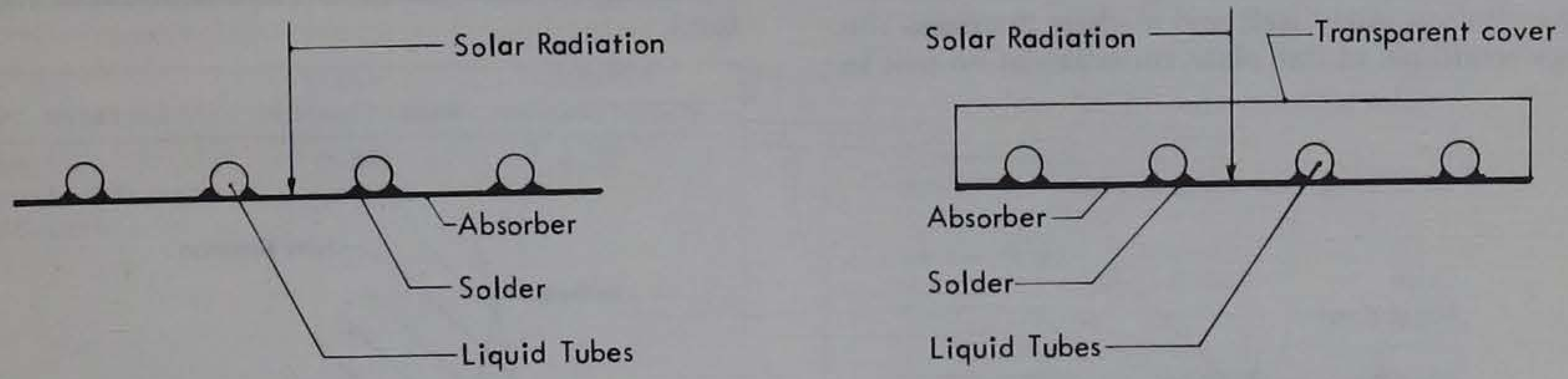
27b. Covered plate collector.



27c. Covered, suspended plate collector.
Airflow under absorber.

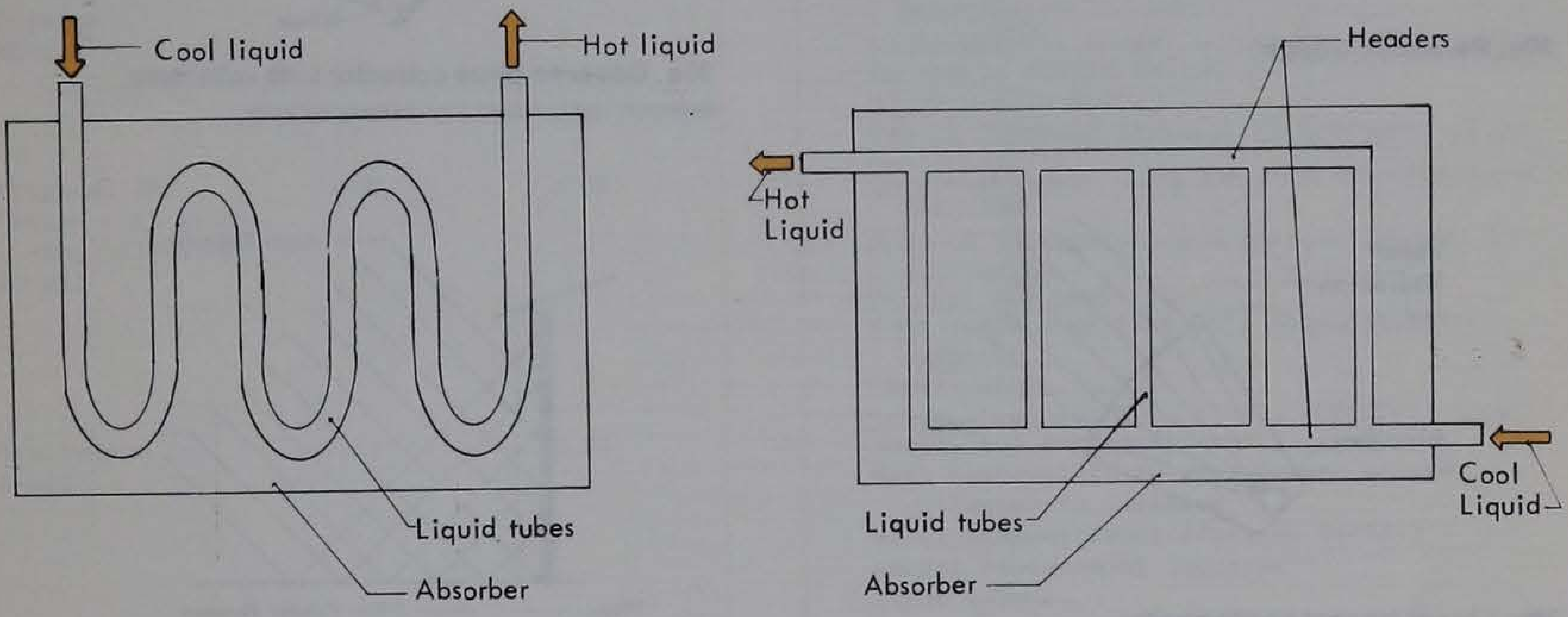
27d. Covered, suspended plate collector.
Airflow both sides of absorber.

Fig 27. Air-type flat plate solar collectors.



28a. Bare plate collector.

28b. Covered plate collector.



28c. Serpentine tube pattern.

28d. Parallel tube arrangement.

Fig 28. Liquid-type flat plate collectors.

Concentrating Collectors

Concentrating collectors have large reflecting surfaces (usually parabolic) or lenses that concentrate solar energy from a large area onto a relatively small absorbing area. Fig 29. Some concentrating collectors heat the fluid in the absorber tube to over 2000 F.

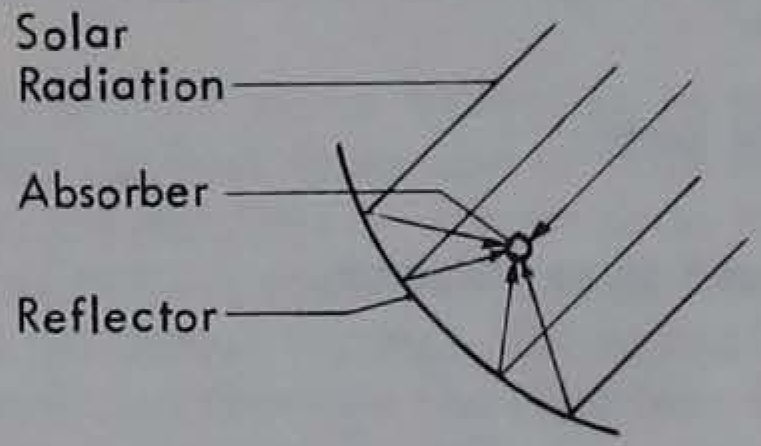
Concentrating collectors use only direct radiation and must be pointed toward the sun to keep the rays focused on the absorber. At least a partial tracking system is required. Because concentrating collectors do not use diffuse radiation, no heat is produced on cloudy days.

Concentrating collectors usually generate steam for industrial processes or run engines. They are expensive, complicated, and difficult to build in farm shops. They have limited usefulness, so far, on the farm.

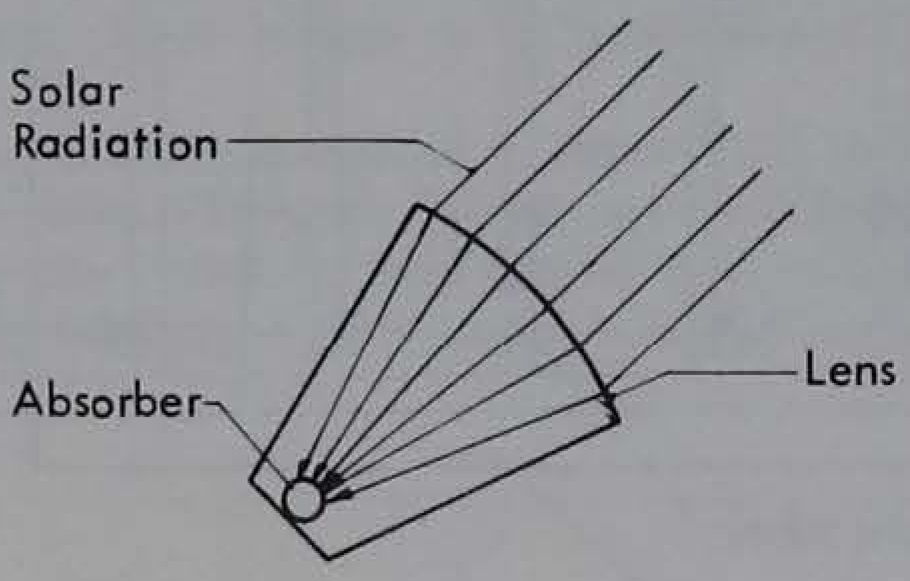
Flat Plate Collectors with Reflectors

These solar collectors have features of both flat plate and concentrating collectors. Reflectors increase the energy intercepting area and concentrate, to an extent, the energy available to a flat plate collector. With reflectors, a flat plate collector can at times produce greater temperature rises.

Reflectors include plywood wings painted white or lined with aluminum foil, concrete slabs painted white, and parabolic sheets lined with aluminized film. Fig 30. Consider the value of the extra energy collected over the life of the reflectors against the cost of the materials and labor required to build and maintain them. For present farm use, reflectors are about break even. They are not recommended unless they also serve some other purpose, such as covering the collector when it is not in use. The two-sided triangular collector with a parabolic reflector may prove to be an exception , Fig 30c , but further research on this system is needed. Fresh snow reflects solar radiation fairly well and slightly increases the energy available to flat plate collectors at no cost to you.



29a. Parabolic trough.



29b. Linear fresnel concentrator.

Fig 29. Types of concentrating solar collectors.

Flat Plate Collector Materials

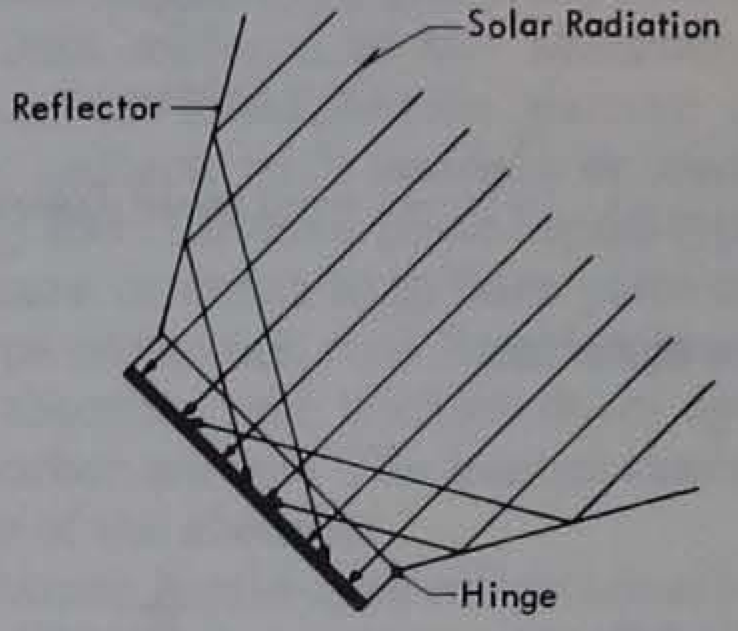
Cover Materials (See Table 15)

Solar collector covers or glazings have three basic purposes:

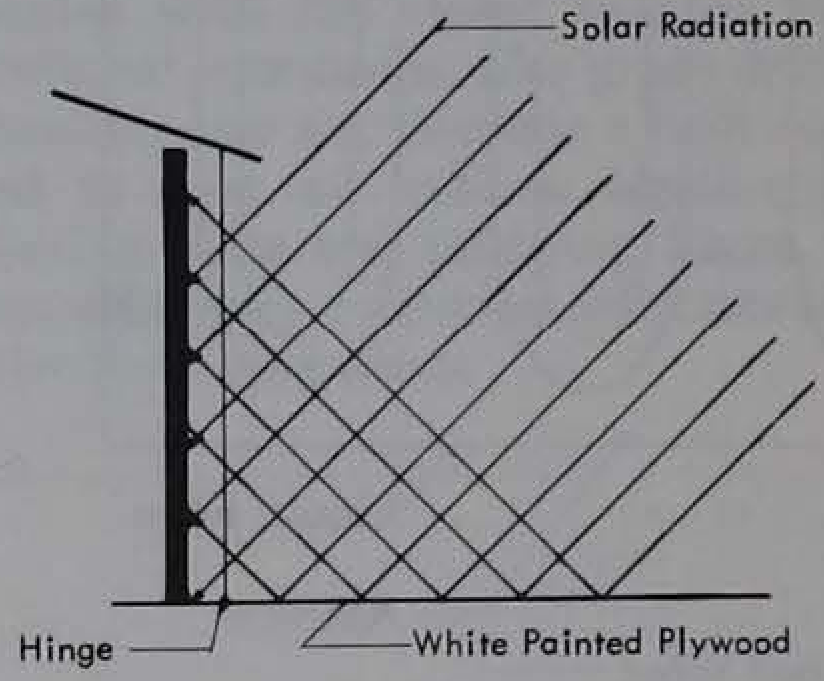
- Reduce convection heat losses by shielding the absorber from the wind;
- Admit solar or shortwave radiation to the absorber;
- Reduce radiation heat losses by preventing the escape of longwave radiation from the collector.

When an absorber is not covered (as in bare plate collectors), much of the absorbed energy is lost again to the wind. Any material that shields the absorber from the wind reduces convection heat losses, but a good cover material also has a high transmittance to shortwave radiation and a low transmittance to longwave radiation.

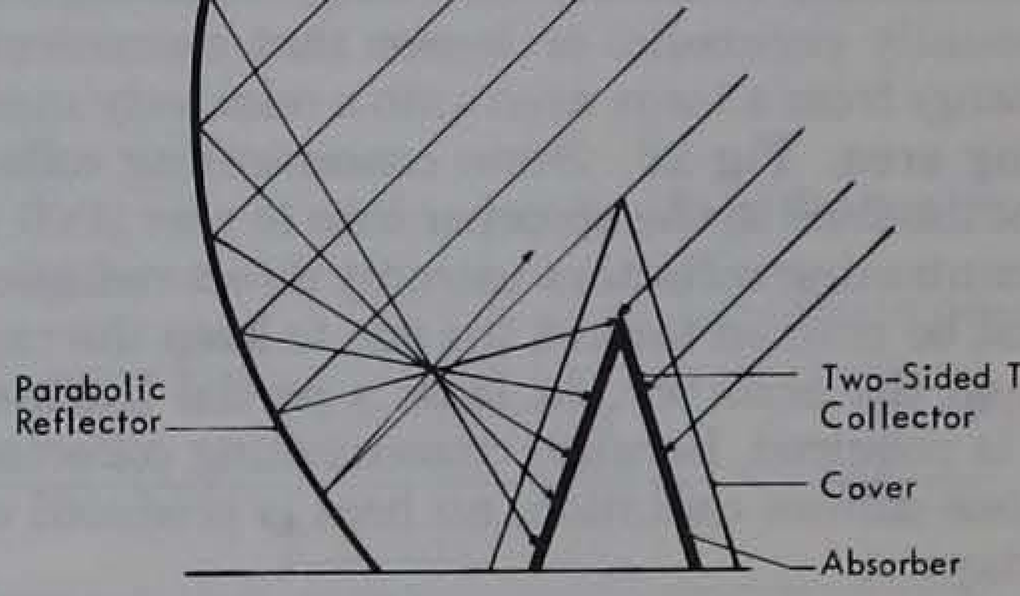
All objects that are warmer than their surroundings lose energy by radiation. Very hot objects, like the sun, radiate mostly high energy waves with short wavelengths. So, most solar radiation is shortwave. Objects only slightly warmer than surrounding temperatures, such as absorber plates in solar collectors, radiate or emit lower energy waves with long wavelengths (also called thermal or infrared radiation).



30a. Covered plate collector with reflectors.
Reflectors can be folded down to cover collector.



30b. Covered plate collector on building sidewall with plywood reflector.
Reflector can be folded up to cover collector.



30c. Two-sided triangular collector with parabolic reflector.

Fig 30. Flat plate collectors with reflectors.

Table 15. Properties of cover materials.

Solar transmittance values are daily averages for incident angles from 0° to 67°.

Costs are relative to polyethylene. Example: polycarbonate costs 125 times as much as polyethylene.

1977 costs—actual and relative costs change over time.

The FRP listed is a clear, nearly see-through fiberglass-reinforced plastic designed for greenhouses and solar collectors.

Cover material	Solar transmittance	Longwave transmittance	Relative cost	Other characteristics
Glass Double-strength 1/8-inch	0.88	0.03	25	Breaks easily, heavy Special expansion gaskets required along frame Sharp edges, especially when broken No static charge buildup Cleans easily Solar transmittance does not change over time Abrasion resistant surface
Flat FRP Regular 25-mil	0.83	0.12	14	Cannot tolerate long exposure to temperatures over 200° Sags when warm, requires closely spaced supports
Flat FRP - Premium 40-mil	0.73	0.06	21	Surface and solar transmittance gradually deteriorate Light weight, tough No static charge buildup Edges easily sealed Can be fastened directly to collector frame
Corrugated FRP Coated with polyvinyl fluoride 40-mil	0.79	0.07	26	Cannot tolerate long exposure to temperatures over 200° Foam or corrugated wood strips required to seal edges. Coating may peel off. More rigid than flat FRP, requires fewer supports Light weight, tough Can be fastened directly to collector frame
Polyethylene 4-mil	0.89	0.80	1	Tough, but punctures easily Very susceptible to wind damage unless collector is inflated Solar transmittance degrades rapidly Annual replacement required Light weight
Polyester Weatherable surface 5-mil	0.87	0.32	9	Flexible film, light weight Vibrates in wind, easily damaged Rapid ultraviolet degradation Not recommended for collectors with single cover
Polycarbonate 1/16-inch	0.84	0.06	125	Punctures easily, especially at low temperatures, but otherwise has durable surface High thermal expansion Solar transmittance slowly deteriorates over time (10% in 7 yr.) Light weight
Polyvinyl fluoride 3-mil	0.91	0.43	9	Hard to handle and install Shrinks at high temperatures; can pull loose from fasteners Light weight Expected life of about 10 yr.

Cover materials that allow shortwaves from the sun to pass, but block longwaves from the absorber, cause the "greenhouse effect." The absorber is warmed by solar energy and the heat is trapped within the collector. An ideal cover material has a shortwave or solar transmittance of 1.0 (100% of the solar radiation reaches the absorber) and a longwave transmittance of 0 (none of the longwave radiation escapes). But, with real materials, part of the incident solar radiation is reflected away and part is absorbed by the cover, and part of the longwave radiation escapes. Short- and longwave transmittances for a number of materials are in Table 15.

The transmittance of a material is not constant. It varies from a maximum at a 0° incident angle to 0 at a 90° incident angle. Less radiation is transmitted through a material at large incident angles because more is reflected off the surface—like a rock skips off a water surface. The transmittance drops off rapidly at incident angles larger than 60°. Because the solar angle of incidence on fixed, flat plate collectors usually exceeds 60° before midmorning and after midafternoon, useful amounts of energy are collected by fixed collectors only during the middle part of the day.

Table 16. Solar transmittance through double-strength window glass.

Incident angle degree	Solar transmittance	
	One layer	Two layers
0° to 20°	0.87	0.77
30	0.87	0.76
40	0.86	0.75
50	0.84	0.73
60	0.79	0.67
70	0.68	0.53
80	0.42	0.25
80	0.00	0.00

Adding cover layers reduces energy losses from a collector, but also reduces the radiation transmitted to the absorber. Each additional layer absorbs and reflects another fraction of the solar radiation.

In addition to good transmittance, other desirable properties of collector cover materials are:

- Resistance to static charges which attract dust (reducing solar transmittance) and make the material difficult to work with.
- High impact strength against hailstones and rocks.
- Resistance to wind damage and abrasion at supports.
- Resistance to deterioration by ultraviolet light.
- Resistance to deterioration at high temperatures. When the fluid is stagnant (not moving) and the sun is shining, temperatures reach 300 F.
- Low coefficient of thermal expansion to reduce sagging at high temperatures, permit wider support spacing, and prevent shrinking away from supports at low temperatures.
- Light weight, for roof mounting.
- Economy. A durable but relatively expensive material may be more economical than a cheaper one requiring annual replacement.
- Ease of installation and maintenance.

Glass is most common on collectors with recirculated working fluids. (See Solar Systems.) It has excellent transmittance that does not change over time. It is rigid and has good abrasion resistance, so it doesn't sag or wear through at supports. Single-strength (0.085" to 0.100" thick), double-strength (0.115" to 0.133" thick), tempered (high-strength), and low-iron glass are available. Low-iron glass has a higher solar transmittance than other glass. The edge of low-iron glass appears water-white rather than the usual greenish-blue.

The biggest disadvantage of glass is brittleness. Rocks, hail, and even stresses caused by expansion and contraction break it. Vertical mounting or a wire-screen cover reduces hail damage, but also the amount of solar energy reaching the collector. The thermal expansion of glass is less than that of wood or steel. Glass attached directly to a wood or steel frame may break when subjected to temperature extremes. Use expansion gaskets between the glass and frame.

A number of transparent plastics can be collector covers. One of these, polyethylene, has a high solar transmittance and very low first cost, and was used on many early collectors. But, it traps little longwave radiation and requires annual replacement. More durable materials are usually selected.

Fiberglass reinforced plastics (FRP) are currently the most popular cover materials for low-temperature agricultural collectors. (Fiberglass reinforced plastic is commonly abbreviated to just fiberglass.) The FRP suitable for solar collectors is not skylight and patio cover material. Its solar transmittance is less than glass, but much better than skylight material. It is clear—almost see-through—and not green, white, or yellow like skylight material. It is sometimes called "greenhouse grade fiberglass."

Because FRP is tougher than glass and expands at nearly the same rate as wood and steel, it is easier to install and can be screwed directly to a collector frame. FRP is more flexible than glass: it can be fastened to curved surfaces, but it requires more support. Corrugated is more rigid than flat FRP, but is harder to seal against air leaks. Use foam rubber or corrugated wood strips.

Heat, ultraviolet light, and moisture cause FRP to gradually deteriorate. Some FRP is guaranteed for 15 to 20 years on greenhouses, but not yet on solar collectors where temperatures are much higher. FRP develops fiber bloom as the binding plastic resin breaks down, exposing the glass fibers. Dirt and fungi trapped among the fibers reduce solar transmittance. In the past, coatings were applied to reduce fiber bloom, but the coating often peeled off.

Other cover materials include polyester, polycarbonate, and polyvinylfluoride. See Table 15. Polyester and polyvinylfluoride are cheaper than FRP and have higher solar transmittance, but they also have higher longwave transmittance, are less durable than FRP, and are harder to work with. Polycarbonate has good transmittance and can withstand ultraviolet radiation better than FRP, but it has high thermal expansion and is very expensive.

Absorber Materials (See Tables 17 and 18)

A good absorber in a solar collector:

- Absorbs a high percentage of incoming solar radiation
- Loses minimum energy to the collector's surroundings
- Efficiently transfers absorbed energy to the collector fluid.

All solar radiation striking an opaque (nontransparent) surface is reflected or absorbed. The fraction that is absorbed (always between 0 and 1) is called the absorptance. The reflected fraction, the reflectance, is 1 minus the absorptance. A good absorber has an absorptance near 1.

Dark surfaces have high absorptances—so paint collector absorbers black if they are not naturally dark. Flat black paints reflect less energy than glossy ones. Select any flat black paint that can withstand temperatures up to 300 F without cracking, peeling, or breaking down. Use an appropriate primer or surface treatment before painting. For new galvanized metal:

1. Clean the metal with a solvent to remove oils.
2. Wash the surface with detergent.
3. Etch the metal with vinegar or muriatic acid.
4. Apply a galvanized metal primer.
5. Apply two coats of flat black paint.

Let the paint dry completely before installing the cover. Some paints give off vapors (called outgassing) as they dry, that can condense on the collector cover and reduce transmittance.

Absorptances for a number of surfaces are shown in Table 17. The solar absorptance of a surface varies with angle of incidence, just as transmittance does. At high angles of incidence a greater percentage of the solar radiation is reflected away. See Table 18.

Table 17. Absorptance and emittance of surfaces.
Normal solar incidence (0° incident angle).

Material	Solar absorptance	Longwave emittance
Flat black paint	0.95-0.99	0.95-0.99
Dark concrete and stone	0.65-0.80	0.85-0.95
Colored paints; brick	0.50-0.70	0.85-0.95
Bright aluminum paint	0.30-0.50	0.40-0.60
Dull metals: copper, brass, aluminum	0.40-0.65	0.20-0.30
Weathered galvanized steel	0.80	0.28
White paint	0.23-0.49	0.92
Copper treated with sodium hydroxide & sodium chlorite	0.89	0.17
Copper, aluminum, or nickel plate with copper oxide coating	0.80-0.93	0.09-0.21

Table 18 . Solar absorptance of flat black paint.

Incident angle degrees	Solar absorptance
0^o-20^o	0.96
30	0.95
40	0.94
50	0.92
60	0.88
70	0.82
80	0.67
90	0.00

Most surfaces with high solar absorptance also have a high longwave emittance. The longwave emittance of a surface (always between 0 and 1) is its tendency to radiate longwave energy. A solar absorber heats to a temperature above its surroundings and then radiates or emits energy as longwave radiation. An ideal solar collector absorber has a longwave emittance near 0.

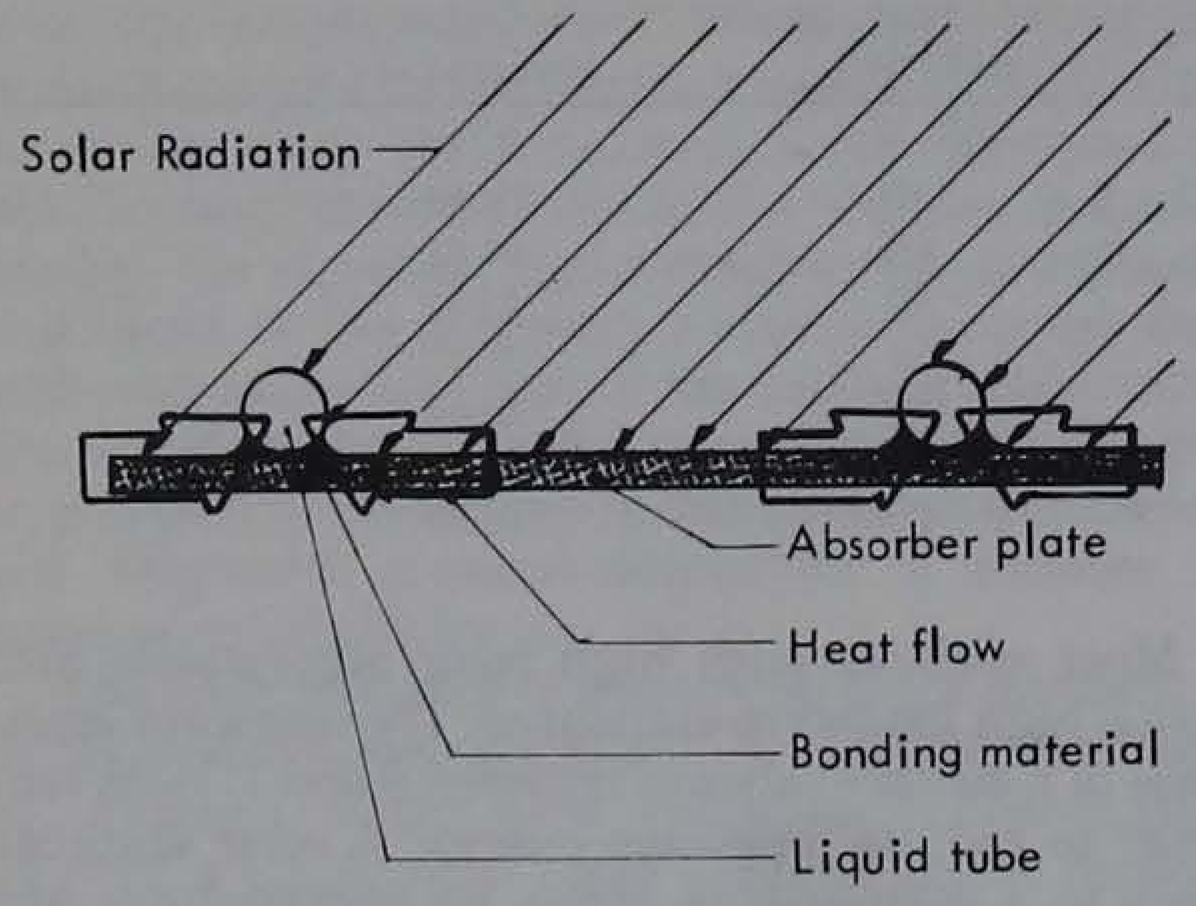
"Selective surfaces" have both high solar absorptance and low longwave emittance. Most of them are special factory-applied coatings. Selective surfaces can reach higher temperatures because they lose less energy by radiation. They increase collector efficiency, but have not yet been widely used on farms. At present costs, commercial selective surfaces are worthwhile only at temperature differences between the collector fluid and outdoor air greater than about 130 F. Most agricultural collectors operate at temperature differences much smaller than this.

Well-weathered galvanized metal with a rough, dull gray surface is a natural mildy selective surface. Table 17 . Painting the metal flat black increases the solar absorptance, but destroys the selective surface—the unpainted surface is probably more cost effective.

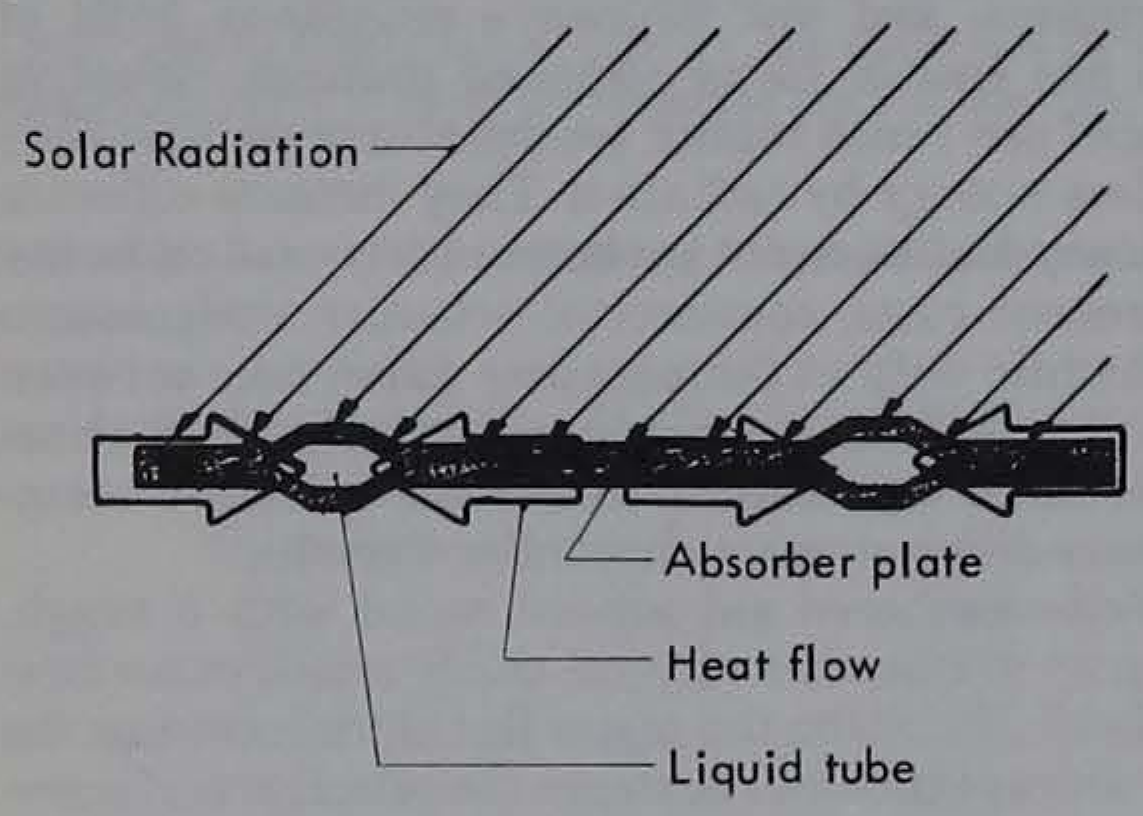
The solar collector absorber must transfer its absorbed energy to the working fluid. In liquid-type collectors, heat moves by conduction through the flat absorber plate to the tubes containing the liquid. Both the absorber and tube materials need high thermal conductivities, and the bond between the tubes and plate must provide a good thermal path. Metals are best, and, the most common in order of increasing conductivity and cost are steel, aluminum, and copper. The metals are painted black or coated with a selective material. Higher absorber conductivity permits greater tube spacing. Plastic absorber plates and tubes are low cost, but have low efficiency and have been used mainly as swimming pool heaters.

The best bonds between metal tubes and absorber plates are solid beads of weld or solder. (The solder must not melt at collector stagnation temperatures.) Clamps, wires, press fits, and spot welds do not provide as good a thermal bond. Bonding is avoided in tube-in-sheet absorbers—the liquid tubes are part of the absorber plate, Fig 31.

Corrosion between dissimilar metals can be a seious problem, especially with copper and aluminum. Consider corrosion problems before installing a liquid solar system.



31a. Tubes bonded to absorber plate.

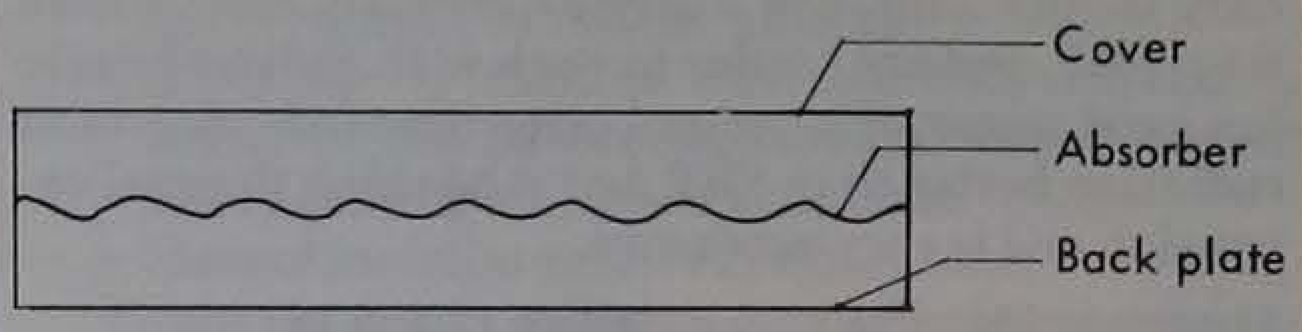


31b. Tube-in-sheet absorber.

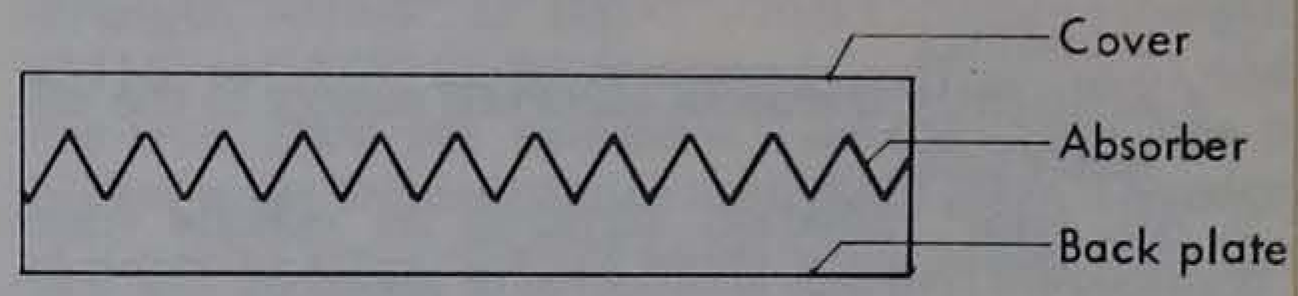
Fig 31. Liquid-type solar collectors.

In air-type solar collectors, the working fluid passes over the entire absorber and picks up heat directly from the surface. In bare and suspended plate collectors, heat must be conducted to the back side of the absorber plate, so it should be made of metal. Absorber plates for other collector types can be of any convenient material: black plastic, plywood or chipboard, roofing metal, concrete, brick, rock, or insulation. The material must withstand the weather and collector stagnation temperatures without sagging or breaking down. Provide a dull, dark surface (paint the surface if it isn't naturally dark).

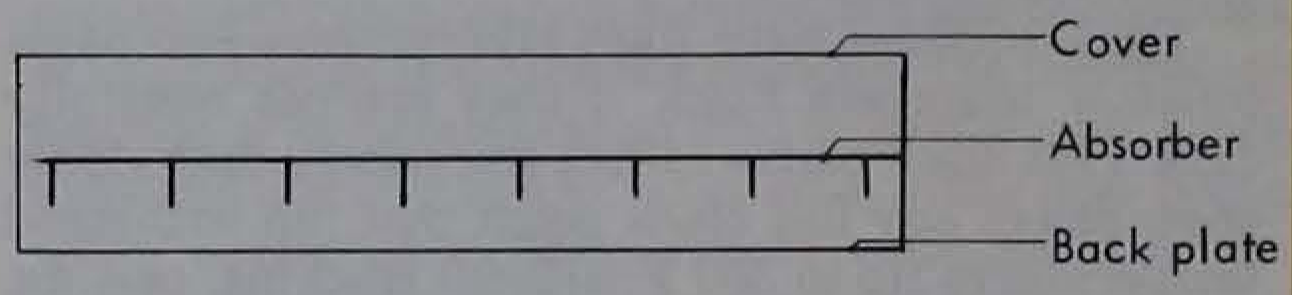
Absorber-to-air heat transfer depends on air velocity and absorber surface area. Up to a point, increasing air velocity improves heat transfer. (See Collector Design.) Increasing the absorber surface area also improves heat transfer. Corrugated, crimped, and finned absorbers have all been tested. See Fig 32. With corrugated absorbers, airflow perpendicular to the corrugations produces slightly better efficiencies than parallel flow.



32a. Corrugated absorber.



32b. Crimped absorber.



32c. Finned absorber.

Fig 32. Air-type suspended plate solar collectors.
Air flow toward the viewer.

Insulation (See Table 19)

In addition to losing heat by radiation, absorbers in solar collectors lose heat to the side and back plates by conduction, natural convection in liquid-type collectors, and forced convection in air-type collectors. The inside walls of the collector warm up and the heat is conducted through them to the outside, where it is carried away by the wind, Fig 33. Insulation reduces these heat losses.

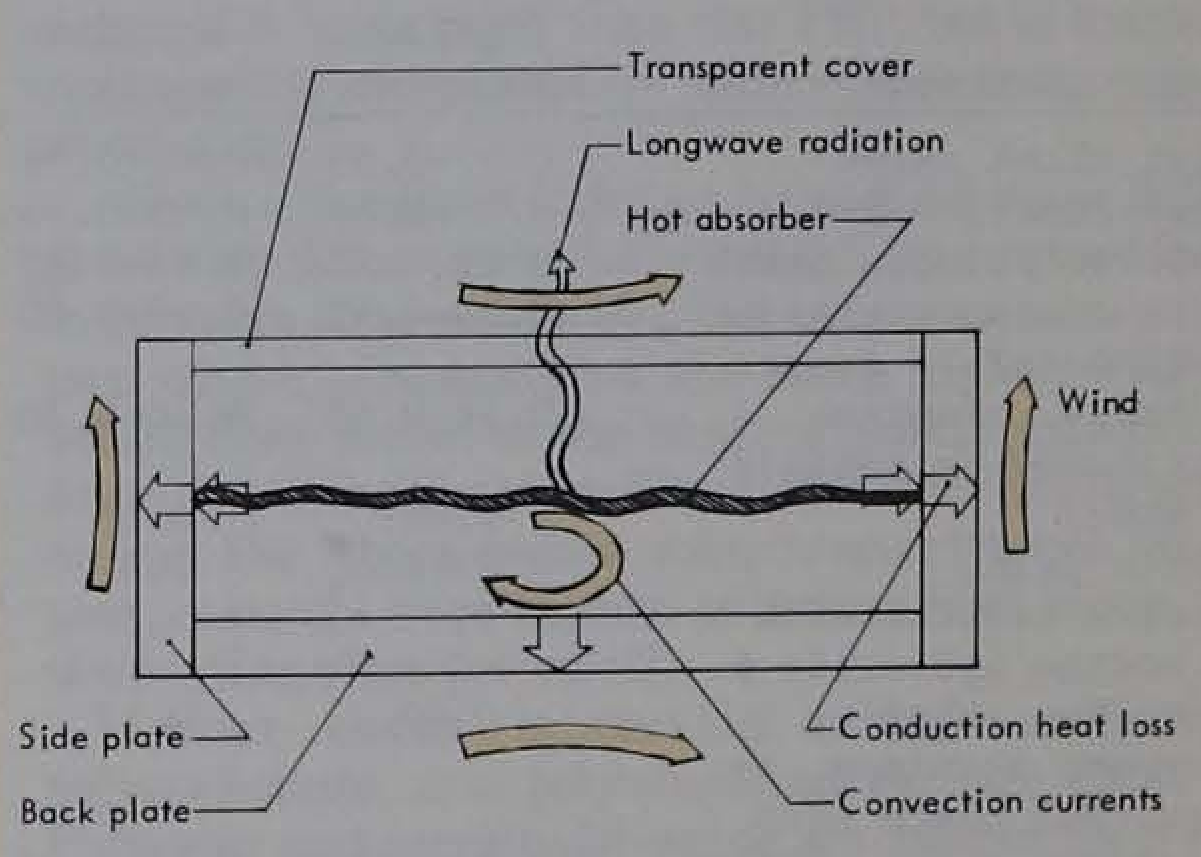


Fig 33. Heat losses from a solar collector.

Because insulation adds to collector cost, use no more than is necessary for your application. Collectors for high air flow, low temperature applications like grain drying require little or no insulation. The R value of wooden side and back plates is high enough for this application. Increasing R from 0.6 (½" plywood) to 4 increases the efficiency somewhat, but probably not enough to pay for the insulation. Increasing R above 4 in a high air flow collector has practically no effect on efficiency. Insulate metal side and back plates in high air flow collectors to about R=2. Insulate collectors for lower air flow, higher temperature applications, like space heating, to about R=6. Insulate ducts or pipes the same as the collector.

Consider these properties of insulation:

- Flammability. Some materials (e.g. polyurethanes) are highly flammable and require fire protection in or near buildings. Consult your insurance company.
- Water resistance. Many insulations lose their insulating value when wet. Protect them from water or use a water resistant type.
- Melting point. Some materials (e.g. polystyrenes) melt below stagnation temperatures. For exposure to high temperatures, use a type with a melting point over 300 F.
- Breakdown temperature. The organic binder in some insulations produces a vapor at high temperatures that condenses on the collector cover and reduces transmittance. Check with the manufacturer. Generally, industrial grade insulations tolerate higher temperatures.

Foil faced, rigid, glass fiber insulation is good inside or outside solar collectors. Other insulations can be used, but special measures may be required to protect them.

Efficiency

Converting solar energy from radiation to heat is not 100% efficient. Tables 22 and 23 show the amount of solar energy available at a collector surface—not the amount of heat available from the collector. Efficiency shows how well a collector converts available solar energy into useful heat energy. Collector efficiency helps you choose among collector types or predict the amount of energy or the temperature rise from a collector. In this handbook:

Collector Efficiency =

$$\frac{\text{Heat energy output over a given time period}}{\text{Solar energy available on the collector surface over the same time period}}$$

Which is equivalent to:

Collector Efficiency =

$$\frac{\text{(Available solar energy) - (Collector energy losses)}}{\text{(Available solar energy)}}$$

Table 19. Insulation values of materials.

From ASHRAE Handbook of Fundamentals, 1977.
Values do not include surface conditions; all are approximate.

		Resistance R	
Material	**Thick.**	**per in. thick 1/k**	**thick. listed 1/C**
Insulation			
Blanket or batt			
Glass wool, mineral wool, or fiber glass		3.50 Approx. read label	
Loose fill			
Glass or mineral wood		2.50 to 3.00	
Vermiculite		2.20	
Shavings, sawdust		2.22	
Milled paper or wood pulp		3.13 to 3.70	
Rigid			
Expanded polystyrene			
extruded		4.00 to 5.26	
molded, 1#′ cu ft		3.57	
Expanded rubber		4.55	
Glass fiber		4.00	
Exp. polyurethane (aged), 1.5#′ cu ft		6.25	
Foamed-in-place urea formaldehyde		4.20 to 5.50	
Building materials			
Building board			
Plaster or Gypsum Board	½"	0.45	
Plywood	⅜"	1.25	0.47
	½"		0.63
Fiber board sheathing	25/32"		2.06
Hardboard, med. density		1.37	
Particle board, med. density		1.06	
Finish flooring			
Carpet + fiber pad			2.08
Carpet + rubber pad			1.23
Floor tile			0.05
Hardwood	¾"		0.68
Masonry			
Brick, common		0.20	
Brick, face	4"		0.44
Concrete block			
Sand and gravel	8"		1.11
	12"		1.28
Lightweight	8"		2.00
	12"		2.27
Lightweight + vermiculite in cores	8"		5.03
	12"		5.82
Concrete, solid		0.08	
Woods			
Hardwoods: maple, oak		0.91	
Softwoods: fir, pine		1.25	
Air film and spaces			
Air space, ¾"-4"			0.90
Interior surface			0.68
Exterior surface			0.17

Notice that: (1) available solar energy is at the collector's tilt angle, and (2) collector efficiency is defined for a specific time period. It is possible to calculate instantaneous, all-day, or even average all-day efficiency over a season for a collector. Because collector efficiency varies with time of day and weather conditions, these three efficiency values usually differ. Know which type of efficiency is being considered when a value is given. See Collector Sizing for examples using efficiency values.

Several factors affect collector efficiency:

- Difference between the average collector fluid temperature and the ambient (outdoor) temperature. The greater this difference, the greater the heat losses. Average fluid temperature approximately equals $\frac{1}{2}$(inlet temp. + outlet temp.). When the inlet temperature is greater than the ambient temperature, heat losses can be high (e.g. when the working fluid is recirculated, see Solar Systems). Heat losses can also be large with high temperature rises through the collector. Temperature rise is affected by the available solar energy and the fluid flowrate.
- Fluid flowrate, which affects exposure of the fluid to the hot absorber. High flowrates reduce exposure time, fluid temperature rise, and heat losses from the collector. High flowrates also increase fluid velocity and improve absorber-to-fluid heat transfer. So, up to a point, higher flowrates improve collector efficiency. Maximum collector efficiency is limited by the cover and absorber properties; once this efficiency is reached, higher flowrates cannot improve it. Also, pressure drop in the collector increases as flowrate increases. Pressure drop measures fluid friction or resistance to flow and requires extra fan or pump power. The selected flowrate must balance these factors.
- Wind speed. Wind increases heat losses and reduces efficiency.
- Insulation, which reduces heat loss. See Insulation.
- Length of fluid flow path through the collector. Up to a point, the longer the fluid is in the collector, the hotter it gets. As length is added to a collector, heat losses eventually increase to equal the solar energy added by the extra area. If a collector is too long, the fluid temperature reaches its maximum part way through the collector and the remaining area is useless.
- Collector type. With the same insulation and fluid flowrates, air-type collectors (Fig 27) in order of increasing efficiency are:
    1) Bare plate
    2) Covered plate, single channel
    3) Covered, suspended plate—air flow above the absorber
    4) Covered, suspended plate—air flow under the absorber
    5) Covered, suspended plate—air flow both sides of the absorber
- Cover transmittance. High solar transmittance and low longwave transmittance increase efficiency. See Cover Materials.
- Number of covers. Multiple covers reduce heat loss, but add cost and reduce solar transmittance somewhat. Most collectors in recirculating systems have two covers; most in single pass systems have one. See Solar Systems.
- Absorber properties. Increase efficiency with high solar absorptance, low longwave emittance (selective surfaces), and absorbers with corrugated, finned, or crimped surfaces. See Absorber Materials.

Maximum efficiency can be achieved only at high cost: multiple low-iron glass covers, selective absorber coatings, high insulation levels, etc. Select only those features needed to maintain reasonable efficiency in your application. Solar collectors that provide service hot water or space heat for homes must operate at low flowrates and high temperature differences. Such collectors are relatively costly. Most agricultural collectors have higher fluid flowrates and lower temperature differences—they can be simple and fairly inexpensive and still operate with good efficiency. Collector efficiencies are included on the collector plans in this handbook.

Solar Energy Storage

Solar energy tends to be most available when you need it least and unavailable when you need it most. The sun shines less than half of each day during the heating season—it may not shine at all for several cloudy days in a row. And, the need for energy is often greatest when the sun is not shining because the air is cool and damp. To save excess solar energy from dry, sunny days for night or cloudy days, install heat storage. Consider the advantages and disadvantages of each heat storage material before choosing one. Table 20.

Table 20. Heat storage materials.

Specific heat is for sensible heat storage.
Glaubers salt melts at 91F and has a latent heat of fusion of 108 Btu/lb.

Material	Weight lb/ft^3	Specific heat Btu/lb-$^{\circ}$F
Water (8.3 lb/gal)	62.4	1.0
Rock (3/4" to 3" diam)	100	0.2
Concrete (solid)	150	0.2
Glaubers salt		
Solid	100	0.5
Liquid	70	0.8

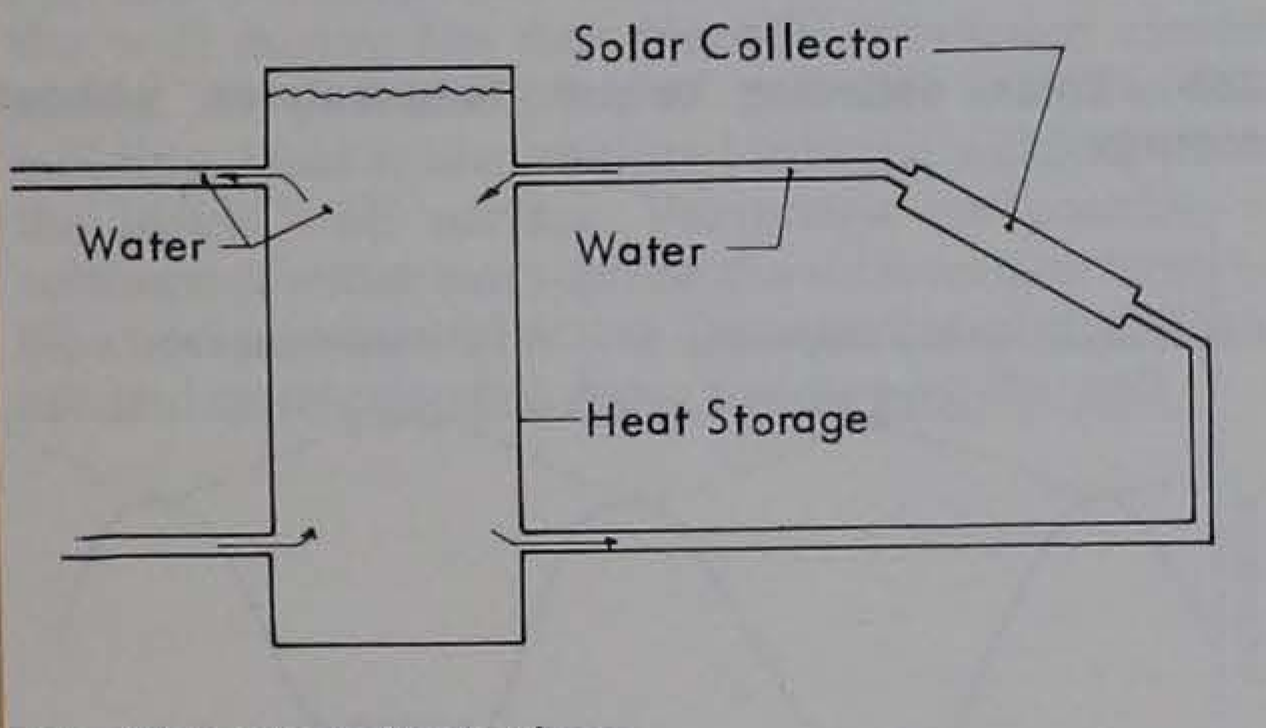
Sensible Heat Storage

You can store solar energy as sensible heat in a large mass of water, rock, concrete, etc. (Sensible heat raises the temperature of a material.) The energy is regained as the material cools. To calculate the amount of energy stored:

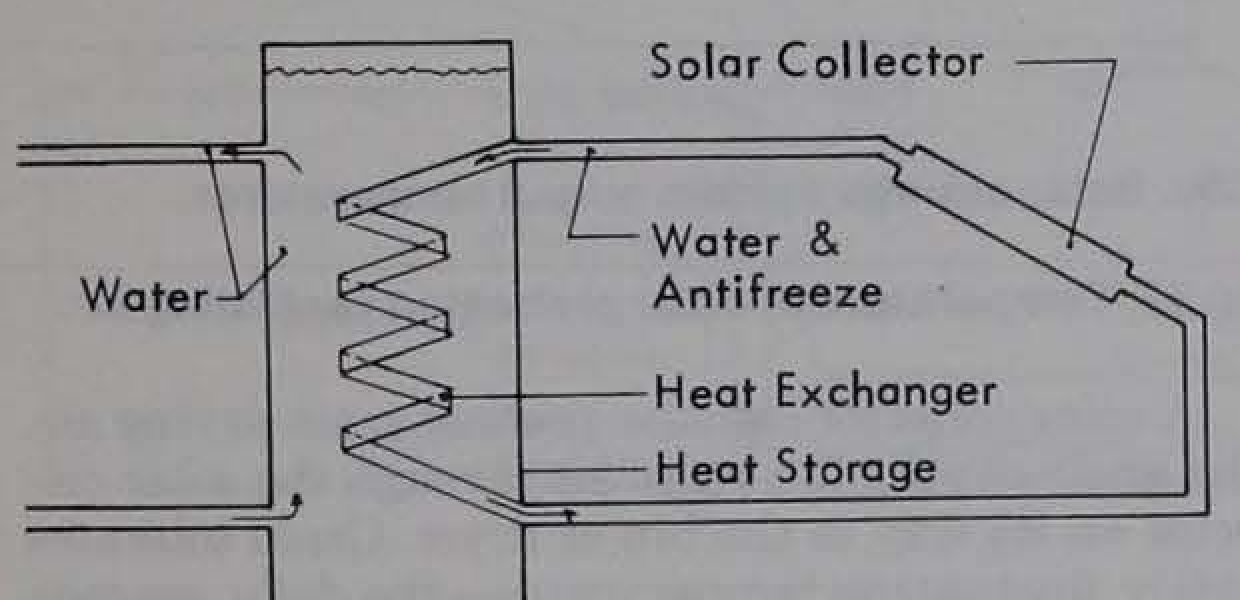
Sensible heat energy (Btu) = Weight of storage material (lb) x Specific heat of storage material (Btu/lb-°F) x Temp rise of storage material (°F)

Specific heat is the energy required to raise the temperature of 1 lb. of material 1°F. (See Table 20.) Keep the storage temperature no higher than necessary for your application to minimize heat loss from storage to its surroundings. Also, keep the volume of storage material as small as possible. For reasonable volume and temperature rise, select a material with high density (mass per unit of volume) and/or high specific heat.

Water is common for liquid solar systems. In warm weather, circulate water from storage through the collector, Fig 34a. To prevent freezing, drain the collector during cold periods with no sun or add antifreeze. In service hot water and some heating water systems using antifreeze, water and antifreeze circulate through the collector and a heat exchanger in the storage tank, Fig 34b. Some efficiency is sacrificed with a heat exchanger, but freezing and drain-down problems are avoided, and little antifreeze is required. Beware of antifreeze leaking into drinking water.



34a. Water in collector loop.



34b. Antifreeze in collector loop.

Fig 34. Liquid solar systems.

Storage tanks must be leak free, corrosion resistant, and able to stand the heat and weight of the hot water. Steel, fiberglass reinforced plastic, and waterproofed concrete have been used. Glass or ceramic-lined tanks are common in service hot water systems. Insulate tanks to at least R = 11; if the tank will be very hot or its surroundings cold, use more insulation.

Example 13: How much energy is stored when 100 ft^3 of water are heated from 50 F to 120 F? (100 ft^3 = 5' x 5' x 4')

Answer: Weight of material = 100 ft^3 x 62.4 lb/ft^3 = 6240 lb

Temperature rise = 120 F - 50 F = 70 F

Sensible heat energy = 6240 lb x 1.0 Btu/lb-°F x 70 F = **436,800 Btu**

(Gal = 6240 lb/8.3 lb/gal = 752 gal)

With an air-to-water heat exchanger, heat from air-type collectors can be stored in water. Generally though, rock or concrete is the heat storage material in air systems. Concrete floors and walls can store heat in passively heated homes, and concrete masonry walls can store heat for livestock buildings. For rock storage, select a rock size between ¾" and 3" diameter; the larger rocks cause smaller pressure drops. Use smooth rock of uniform size and construct the bed with a large face area and relatively short depth in the airflow direction.

Example 14: How much energy is regained from a 100 ft^3 rock bed cooled from 120 F to 50 F?

Answer: Weight of material = 100 ft^3 x 100 lb/ft^3 = 10,000 lb

Temperature drop = 120 F - 50 F = 70 F

Sensible heat energy = 10,000 lb x 0.2 Btu/lb-°F x 70 F = **140,000 Btu**

Note that rock stores less heat per cubic foot than water. Potential problems with rock beds include dust accumulations, water condensation in the bed, and algal growth on the rocks.

The storage container is usually of lumber or concrete and must be air-tight and able to support the weight and lateral pressure of the rock bed. Insulate the rock bed the same as a hot water storage tank.

Latent Heat Storage

When a solid is heated, its temperature rises until it reaches the melting point. At the melting point, any added energy (latent heat of fusion) changes the material from the solid phase to the liquid phase without raising its temperature. The same quantity of heat is released when the material freezes from a liquid back into a solid. A number of salts (phase change salts) have melting points and heats of fusion in a range that makes them useful for storing energy in solar heating systems. One of these, Glaubers salt ($Na_2SO_4 \cdot 10H_2O$, sodium sulfate decahydrate), melts at 91 F. Its other properties are listed in Table 20.

Stacks of small, plastic containers of phase change salt make up a latent heat storage bed. The working fluid passes through spaces between the containers. The containers are sized for the liquid volume because the salt expands when it melts. The containers and spaces between them occupy about twice the volume of the liquid salt.

Example 15: How much energy is released when a 100-ft^3 bed of liquid Glaubers salt cools from 120 F to 50 F?

Answer: Actual liquid volume = $\frac{1}{2}$ x 100 ft^3 = 50 ft^3

Weight of material = 50 ft^3 x 70 lb/ft^3 = 3500 lb

Sensible heat, liquid = 3500 lb x 0.8 Btu/lb-°F x (120 F - 91 F) = 81,200 Btu

Latent heat = 3500 lb x 108 Btu/lb = 378,000 Btu

Sensible heat, solid = 3500 lb x 0.5 Btu/lb-°F x (91 F - 50 F) = 71,750 Btu

Total heat energy = 81,200 + 378,000 + 71,750 = **530,950 Btu**

More energy can be stored in a cubic foot of phase change salts than in rock or water. See examples and Table 20. And, a lot of heat energy can be removed from or added to storage without changing the storage temperature. In Example 15, 378,000 Btu are removed from storage while the temperature stays at 91 F. With sensible heat storage, the storage temperature and heating system performance drop as heat is removed. The advantages of phase change salts are offset by their high cost and uncertain life. Some salts tend to break down and do not completely freeze after a number of freeze-thaw cycles.

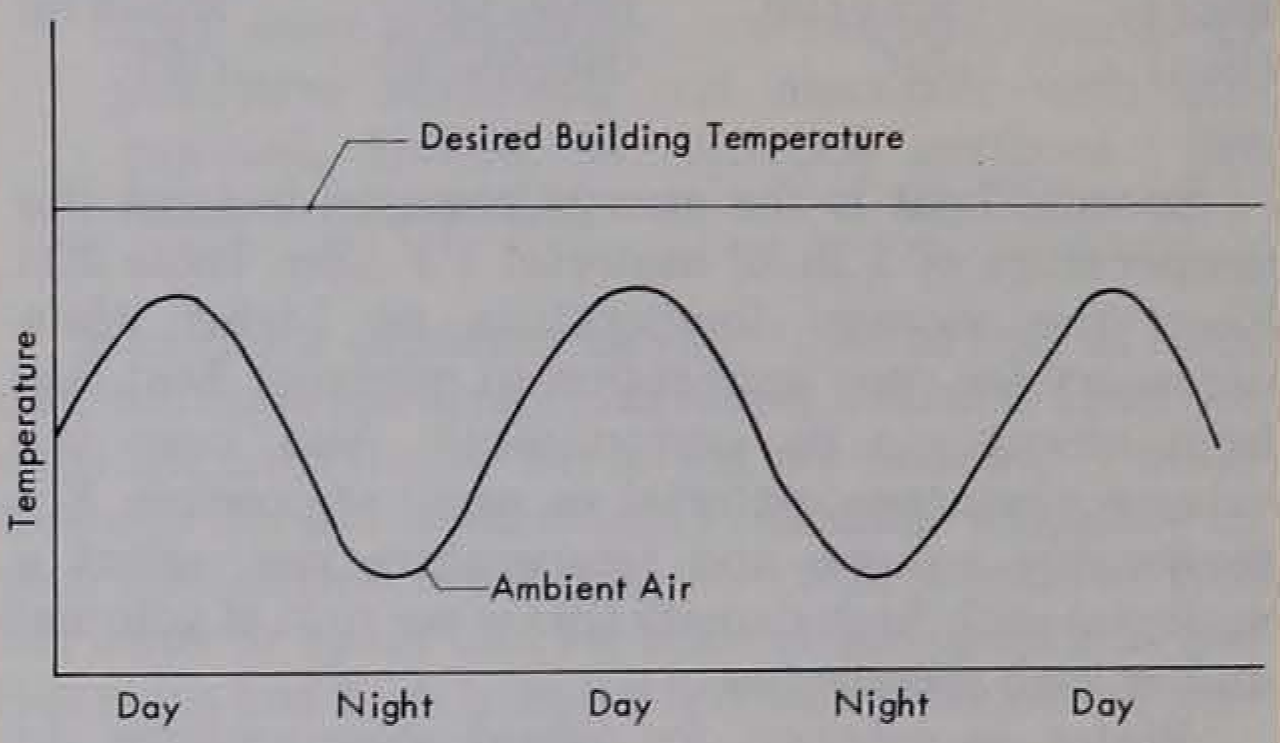
Utilizing Heat Storage

In the North Central Region, a solar heating system needs a very large solar collector and storage volume to meet 100% of a building heating load. The few times a year that such a large system is needed may not justify its cost. Systems with storage are usually designed to provide enough heat for one cloudy day and then a backup heater takes over. Although the heater runs less often when storage is included in the solar heating system, it must be full-sized. On cold, cloudy days after stored heat is depleted, the backup heater must handle the full heating load.

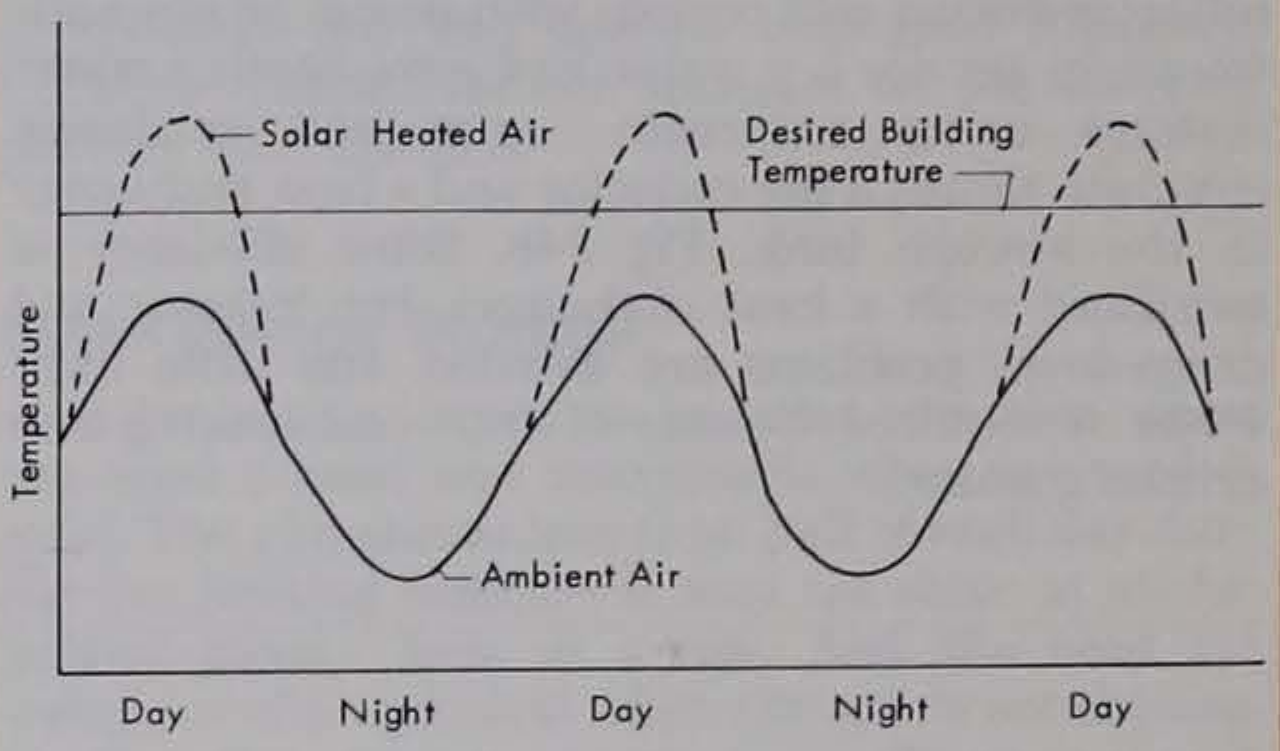
In solar energy systems that simply preheat ventilating air for a livestock building, heat storage produces a time lag in the delivery of solar heat. During the day, warm ambient air plus solar energy warm the storage material. Later, the cool night air removes heat from storage to help maintain the building temperature. The heat storage unit has two effects:

(1) It smooths out the wide fluctuations in solar heated air temperatures, Fig 35. A solar collector without storage increases natural day-night temperature fluctuations.

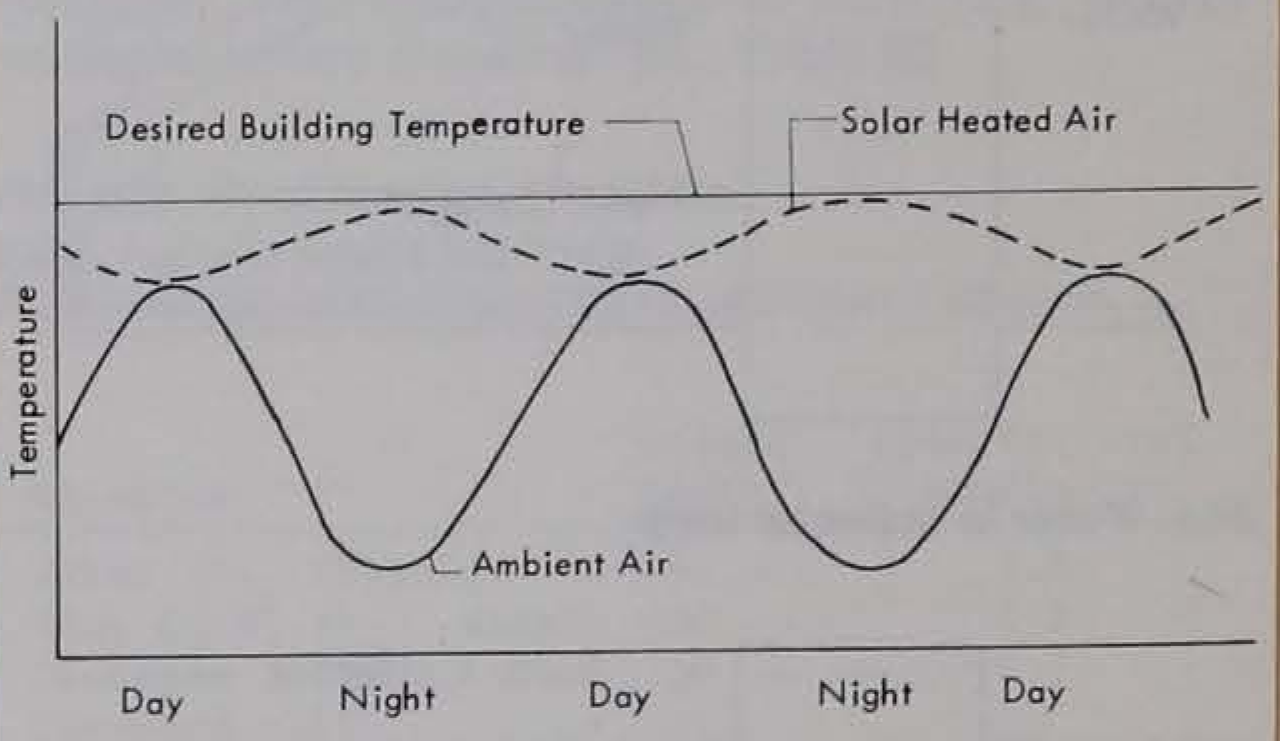
(2) It increases the number of days that solar energy can heat the building. In winter, air leaving the solar collector may be below the desired building temperature, even on sunny days. But on sunny spring and fall days, a solar system without heat storage can overheat the building, so the system must be bypassed. With properly sized heat storage, however, the extra daytime heat is stored until evening, and the solar system can operate all day. A greater total amount of energy is collected and more fuel is saved by the solar system.



35a. Typical day-night ambient temperatures.



35b. Solar collector output temperatures without storage.



35c. Solar storage system output temperatures.

Fig 35. Temperature of solar preheated ventilating air.

A solar collector can also preheat grain drying air. The grain-drying fan pulls air through the solar collector on its way to the bin or dryer. Grain tolerates widely fluctuating temperatures—the daily average temperature is important, not the high or low. The grain itself stores solar energy. When solar-heated air enters the bin, grain at the bottom is warmed and slightly overdried. The bottom grain warms and even dries night air and drying continues up through the bin. Multi-use collectors with heat storage can dry grain, but solar systems built only for grain drying do not need heat storage.

Desiccant Materials

Solar energy can also be stored as drying potential in desiccants, which is useful for grain drying. A desiccant can remove moisture from, or dry, another material. Solar heat energy removes moisture from the desiccant material and then the desiccant removes moisture from the grain drying air or the grain itself.

In one desiccant system, overdried corn is the desiccant. Part of the previous year's corn is kept in the bin and dried below 10% with solar heat, and then used to dry new corn in the fall. See Desiccant System.

Solar Systems

There are two basic types of solar systems—passive and active.

Passive Systems

In passive solar systems, the working fluid moves with little or no pump or fan power. Natural convection and radiation distribute the collected solar energy.

The Trombe wall is one example of a passive solar heating system, Fig 36. The heart of the system is a massive concrete or masonry wall on the south side of the building. The outside of the wall is painted black and has a transparent cover. Solar radiation warms the wall during the day. Natural convection moves heated air past the front of the wall and into the building. Heat is also radiated into the building from the inside wall surface. Variations are possible—columns of water can replace the solid wall, or in combination passive and active systems, fans rather than natural convection can move the air past the wall.

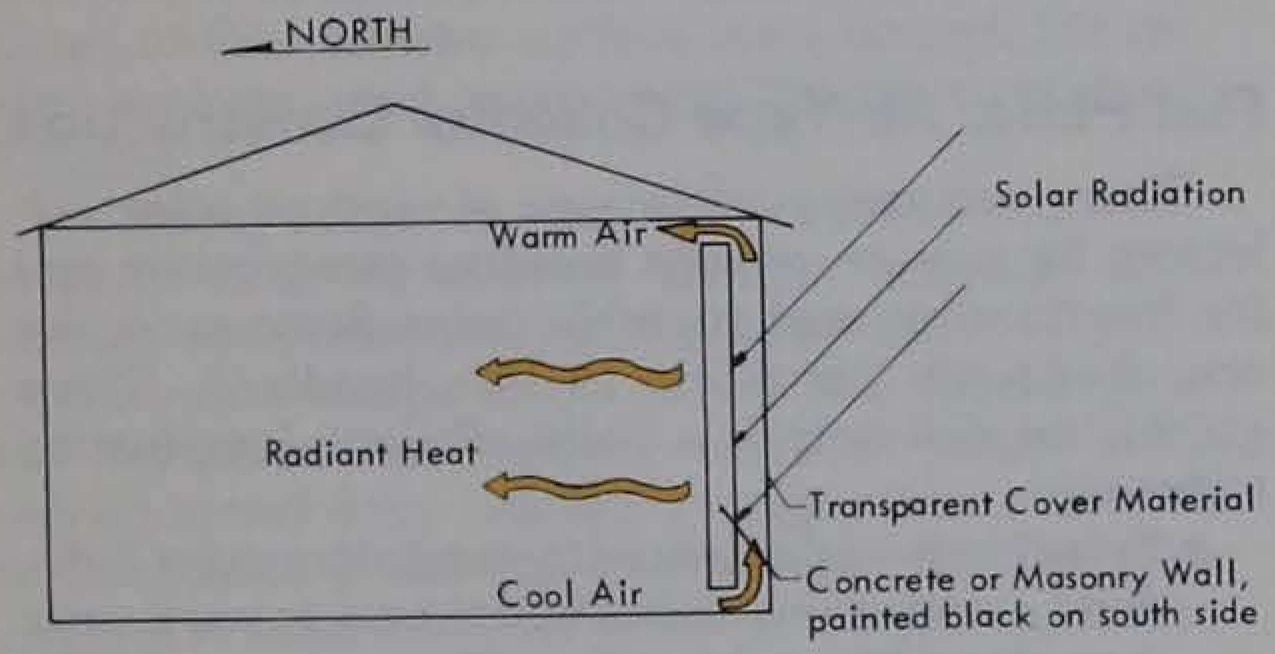


Fig 36. Passive solar heating with a Trombe wall.

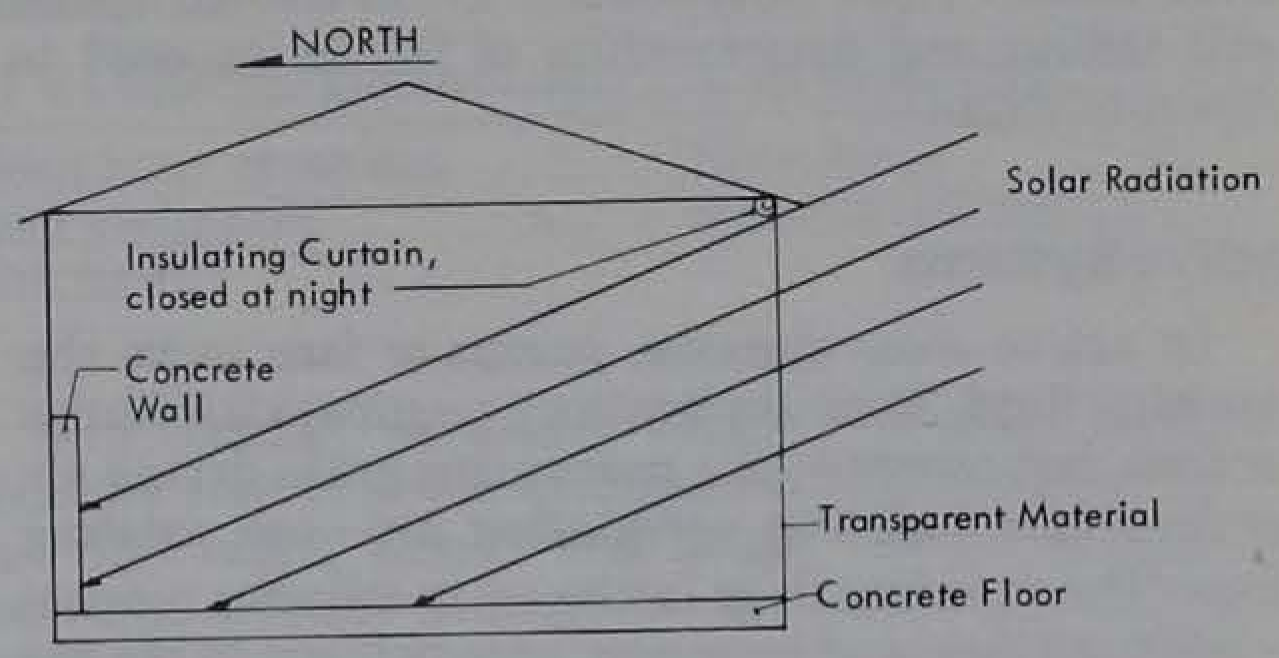


Fig 37. Passive solar heating by direct gain.

Direct gain solar heating is also passive, Fig 37. Solar energy entering the building through south windows is absorbed by the materials inside. At night, these materials help keep the building warm. Heating is more effective if the back wall and floor of the structure are concrete. Window area is based on the heating needs for an average winter day. With direct gain heating, insulate the south windows at night or you will lose as much heat as you gained during the day. South facing, open front livestock buildings utilize simple direct gain solar heating with a roof overhang that allows the winter sun to penetrate, but keeps the summer sun out, Fig 38.

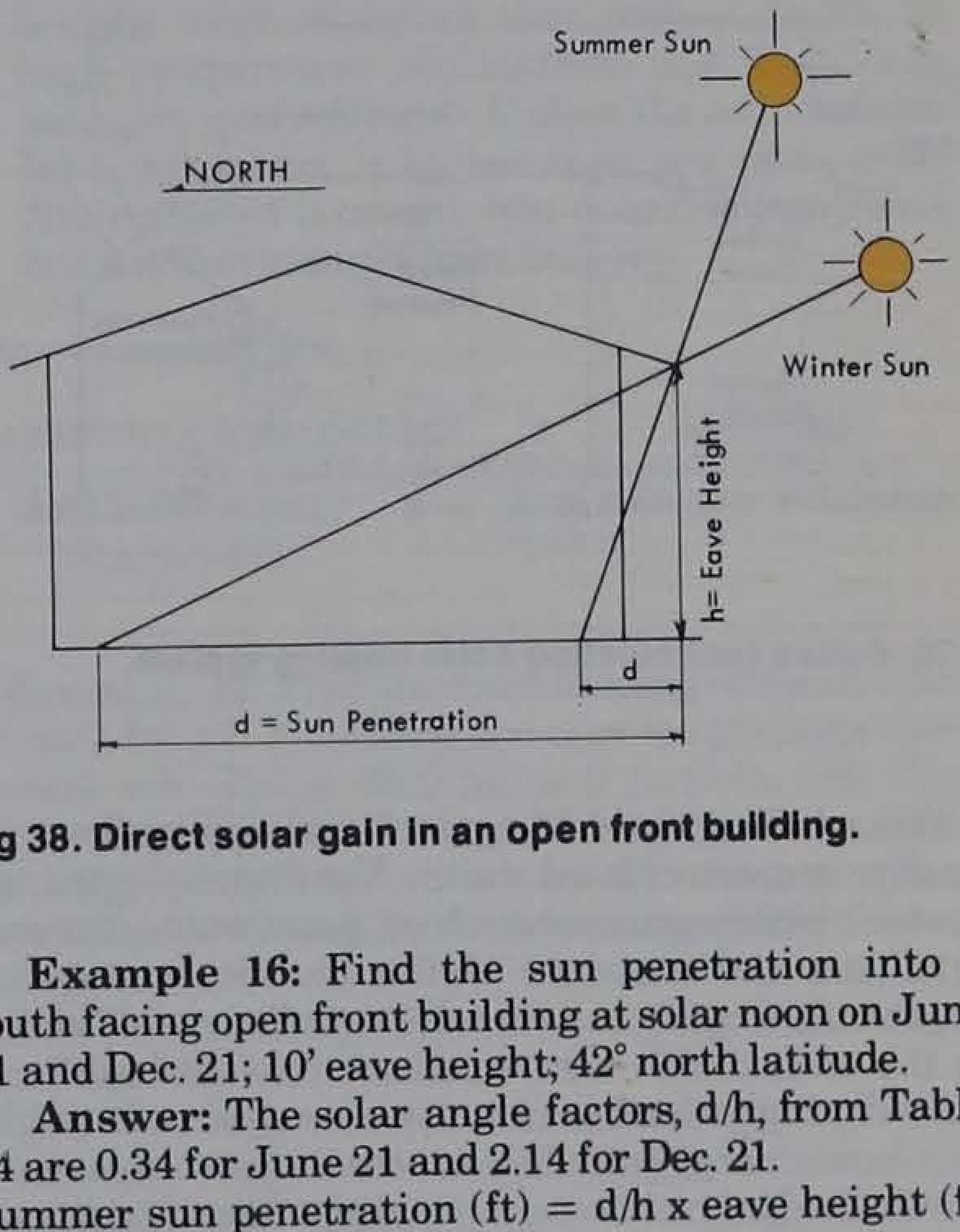


Fig 38. Direct solar gain in an open front building.

Example 16: Find the sun penetration into a south facing open front building at solar noon on June 21 and Dec. 21; 10' eave height; 42° north latitude.

Answer: The solar angle factors, d/h, from Table 14 are 0.34 for June 21 and 2.14 for Dec. 21.
Summer sun penetration (ft) = d/h x eave height (ft) = 0.34 x 10' = **3.4 ft**
Winter sun penetration (ft) = 2.14 x 10' = **21.4 ft**

Sun penetration is less at solar noon than in the morning or afternoon because the sun reaches its maximum altitude at solar noon.

Passive solar systems can be simple and can provide heat at low operating and maintenance costs. Disadvantages include poor temperature control, wide temperature fluctuations in the heated space, and fading and deterioration of fabrics exposed to direct sunlight.

Active Systems

In active solar systems, pumps or fans move the working fluid. Some applications require extra pumps or fans, but others—like preheating grain drying air or livestock building ventilating air—use existing fans. The pressure drop in the solar collector reduces system airflow and increases energy input to the fan motor.

Some active systems are closed—they recirculate the same air or liquid through the solar collector. Recirculating systems, Fig 39, mainly heat shops, homes and service hot water. Fluid entering the collector is usually above ambient temperature. High output temperatures can be obtianed, but only high quality collectors maintain good efficiency. Seal air recirculating systems tightly to prevent infiltration of cold air and loss of efficiency. Also, avoid running the collector if the inlet fluid is hotter than the absorber, or heat will be lost from the system. Install a differential thermostat to sense fluid and absorber temperatures and control the pump or fan in the collector loop.

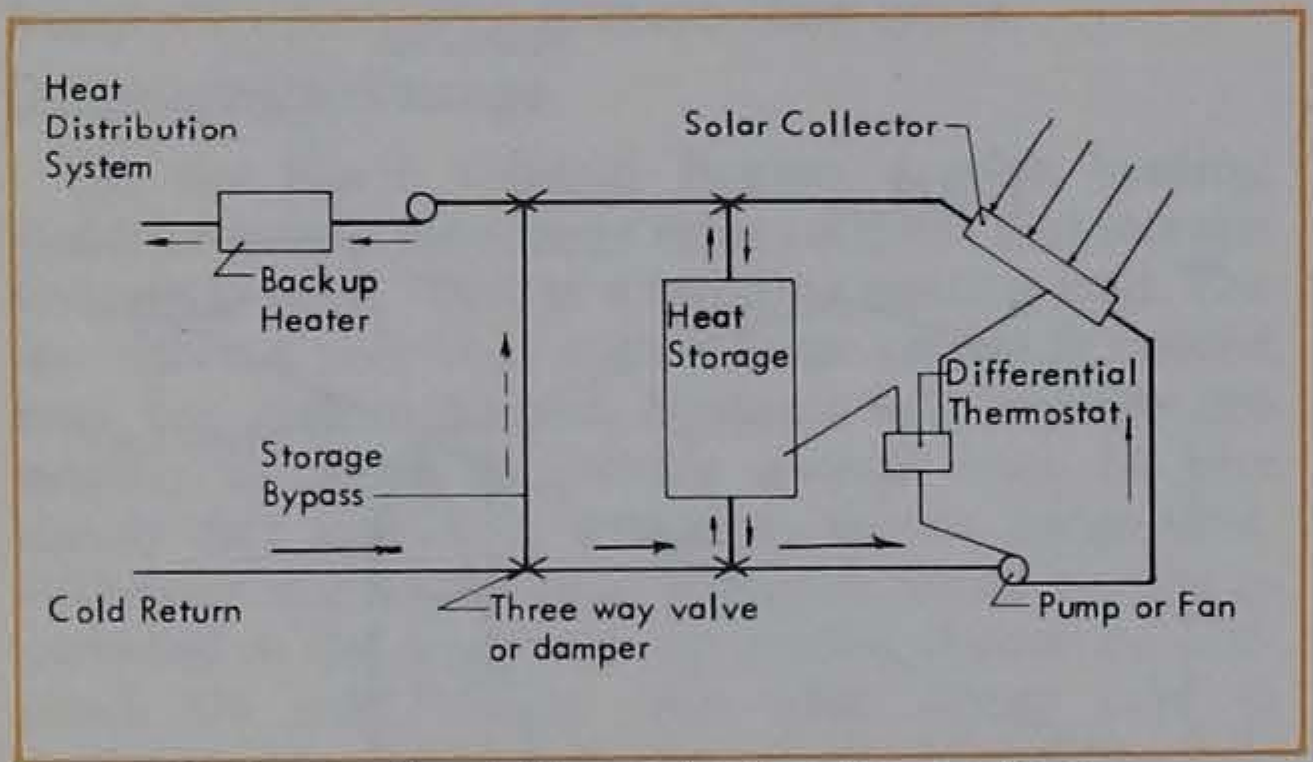


Fig 39. Active recirculating solar heating system.

The working fluid in agricultural applications is usually unrecirculated air. Ventilating air in livestock buildings removes dust, gases, odors, disease organisms and moisture. Although heat energy is lost, ventilating air is not recirculated to avoid bringing the undesirable elements back into the building. Grain drying air removes moisture—again, although some heat energy may be lost, the exhaust air is not recirculated to avoid rewetting grain. Also, dust in exhaust air from livestock buildings and grain bins would soon coat the solar collector cover and absorber, reducing efficiency.

Solar collectors in nonrecirculating systems preheat the working fluid, Fig 40. Heat storage can smooth out temperature fluctuations in the solar heated air, Fig 35, and, if necessary, a backup heater can boost the temperature to a desired level.

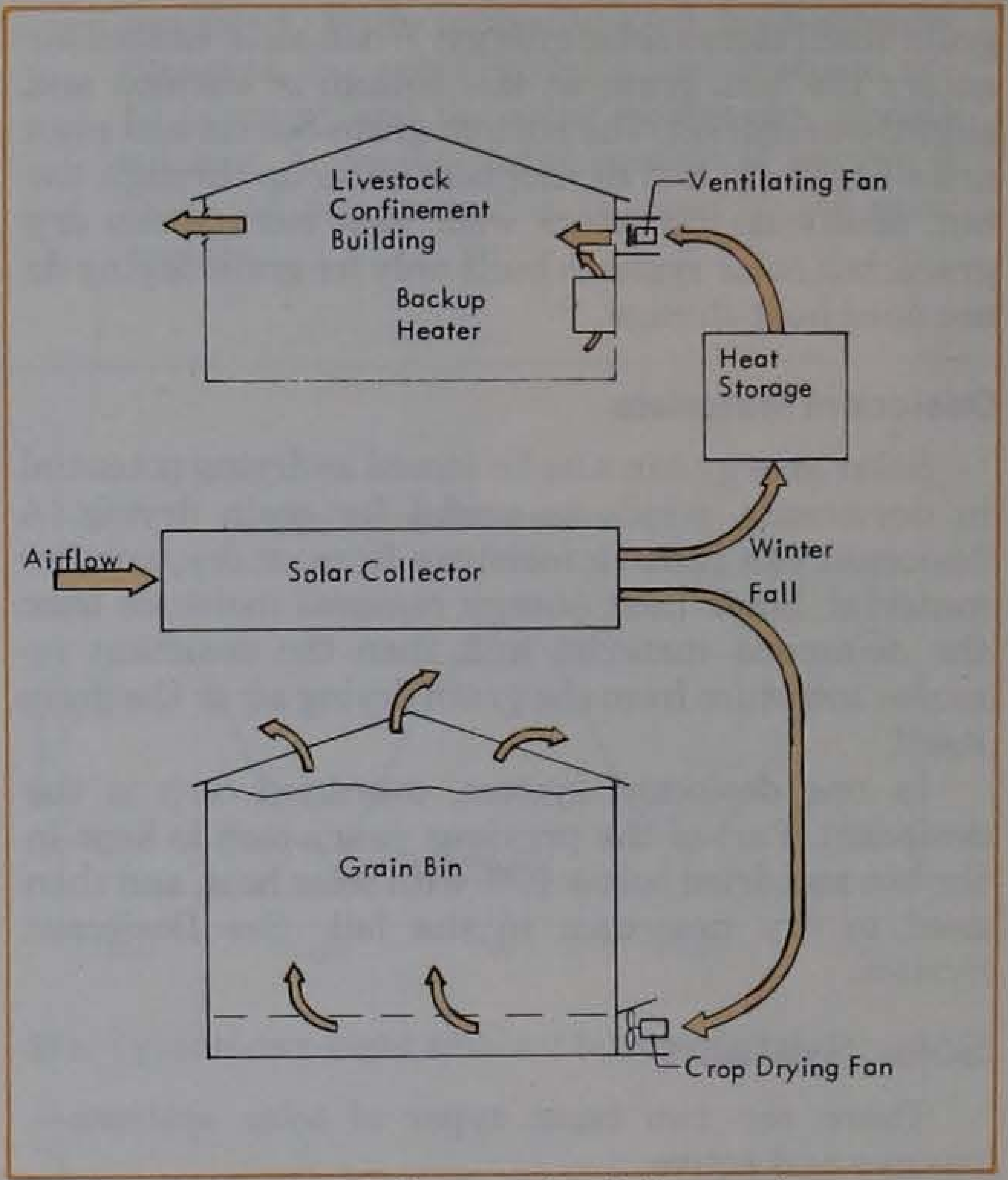


Fig 40. Solar preheated nonrecirculating system.

The collector inlet fluid is at the ambient temperature in nonrecirculating air systems and farm systems typically use low temperature rises. Thus, the difference between ambient and average fluid temperatures is usually small. Simple collectors can operate at high efficiency. Efficiency is best if all the air goes through the collector, but excessive pressure drops can resuslt. Bypass the collector with part of the air to limit pressure drop in the collector to about $^{1}/_{4}$" of water for grain drying and $^{1}/_{8}$" for ventilating air.

Temperature rise of mixed airstream =

$$\frac{\text{Solar heated airflow (cfm)}}{\text{Total airflow (cfm)}} \times \begin{array}{c}\text{Temp rise of solar}\\ \text{heated airstream}\end{array}$$

Flat Plate, Air-Type Collector Construction

There are many variations of air-type solar collectors for new or retrofit building construction and for freestanding and portable units. Some examples are shown in the plans in this handbook. These guidelines will help you build efficient, long-lasting collectors:

- Select materials that: withstand ultraviolet light, heat, wind, snow, and rain; are easy to work with; have long life and low cost. Many common building materials (sheet metal, chipboard, plywood, dimension lumber) are adequate.

- In collectors with distinct air channels, keep collector air velocity between 500 fpm and 1000 fpm. Air velocity (fpm) =

$$\frac{\text{Airflow through collector (cfm)}}{\text{Collector cross-sectional area (ft}^2\text{)}}.$$

  At air velocities under 500 fpm, simple collectors are inefficient; above 1000 fpm, pressure drop is usually too high.
- Keep air velocity below 1000 fpm in ducts. Provide at least 1 ft^2 of duct cross-sectional area for each 1000 cfm.
- Keep total solar system (collector and ducts) pressure drop less than 1/2" of water for grain drying air. Greater pressure drops reduce fan performance too much. If your pressure drop is excessive, bypass the solar system with part of the air. (Pressure drop is the difference between the inlet and outlet air pressure. In grain drying systems where the fan draws ambient air through the collector, the inlet pressure is 0—just measure the negative pressure at the entrance to the fan.)
- Cover air inlets with 1/4" hardware cloth to keep out birds, rodents, and trash.
- Use treated lumber for components in contact with the soil.
- Seal the collector to prevent air leaks. Caulk joints and cracks with silicone or butyl rubber and seal cover-sheet laps with clear silicone. Seal the edges of corrugated materials with corrugated wood or foam rubber strips.
- Fasten FRP with screws rather than nails.
- Position rows of portable or freestanding collectors so they do not shade one another.
- If collectors are not used during the summer, shade them from the sun or open vents (1 sq. ft. of vent opening per 100 sq. ft. of collector surface area) to keep them cool. Locate vent openings so prevailing winds or natural convection (i.e., top and bottom of the collector) cool the collector.

Collector Sizing

The decision whether or not to use solar energy can depend on the size of the collector you need. First, the total cost of a solar installation is directly related to the collector surface area. Second, the collector area required may exceed the space you have available.

Calculate collector size for (a) maximum temperature rise, (b) desired 24-hour average temperature rise, or (c) average heating load.

Maximum temperature rise is the difference in fluid temperatures (outlet - inlet) at about solar noon on sunny days. (Measure temperature rise with the fan running and the thermometer shaded.) Use it to size a solar collector when a specific noon-time temperature is desired or the fluid temperature has a maximum limit. Use clear day insolation in the calculations, Table 22, appendix.

Collector area (ft^2) =

$$\frac{1.1 \times \text{Collector airflow (cfm)} \times \text{Max. temp. rise (°F)}}{\begin{array}{c}\text{Noon hour, clear day}\\ \text{solar radiation}\\ \text{(Btu/hr-ft}^2\text{)}\end{array} \times \begin{array}{c}\text{Noon hour}\\ \text{collector efficiency}\end{array}}$$

You cannot measure 24-hour average temperature rise. It is the average rise over a season—day and night, cloudy and bright—in an average year. The 24-hour average for the season is roughly 0.1 to 0.2 times the maximum temperature rise. Use the 24-hour average temperature rise to size a collector if the average rather than the maximum temperature rise is important (e.g., grain drying). Use average daily insolation in the calculations, Table 23, appendix.

Collector area (ft^2) =

$$\frac{1.1 \times \begin{array}{c}\text{Collector airflow}\\ \text{(cfm)}\end{array} \times \begin{array}{c}\text{Avg. temp. rise}\\ \text{(°F)}\end{array} \times \begin{array}{c}24\\ \text{(hr/day)}\end{array}}{\begin{array}{c}\text{Avg. solar energy}\\ \text{(Btu/day-ft}^2\text{)}\end{array} \times \text{Avg. collector efficiency}}$$

Use average heating load to size:

- Solar systems with heat storage to meet nightime or constant daytime heating loads.
- Simple solar collectors that preheat fluids for high temperature applications (e.g., high temperature grain drying). Unless the collector outlet temperature is higher than you need, every Btu collected is useful. Btu output is important, but not the timing of heat delivery.

Collector area (ft^2) =

$$\frac{\text{Avg. heating load (Btu/hr)} \times \text{24 (hr/day)}}{\begin{array}{c}\text{Avg. solar energy}\\ \text{(Btu/day-ft}^2\text{)}\end{array} \times \text{Avg. collector efficiency}}$$

Example 17: Find the freestanding collector surface area for a 5 F, 24-hour average temperature rise for solar stir drying 5500 bu near Lincoln, NE. The grain will be dried in Oct. and Nov. at 1 1/4 cfm/bu. The collector tilt angle is latitude + 15°. Also, size the electric heater to produce the same temperature rise.

Answer:

(1) The freestanding collector plan gives the average all day efficiency as 60%.

(2) Average daily solar data for Lincoln are in Table 23i, appendix. The average energy available on a latitude + 15° surface during the drying period:
Oct.—1688 Btu/day-ft^2
Nov.—1354 Btu/day-ft^2

$$\text{Avg} = \frac{1688 + 1354}{2} = 1521 \text{ Btu/day-ft}^2$$

(3) Collector airflow (cfm)
= 5500 bu x 1.25 cfm/bu = 6875 cfm

(4) Collector area (ft^2)

$$= \frac{1.1 \times 6875 \text{ cfm} \times 5\text{F} \times 24 \text{ hr/day}}{1521 \text{ Btu/day-ft}^2 \times 0.60}$$

= 994 ft^2
= about **1000 ft^2**

(5) Daily energy production (Btu/day)

$$= \text{Collector area (ft}^2) \times \underset{(\text{Btu/day-ft}^2)}{\text{Avg. solar energy}} \times \text{Collector efficiency}$$

= 1000 ft^2 x 1521 Btu/day-ft^2 x 0.60 = 912,600 Btu/day

$$\text{Electricity (kWh/day)} = \frac{912{,}600 \text{ Btu/day}}{3{,}412 \text{ Btu/kWh}}$$

= 267 kWh/day (Table 21)

$$\text{Heater size (kW)} = \frac{267 \text{ kWh/day}}{24 \text{ hr/day}} = \mathbf{11.1\ kW}$$

Table 21. Heating values of fuels.
A standard cord of wood is 8' long, 4' high, 4' wide.

Fuel	Heating value	Typical heater efficiency, %
Natural gas	1000 Btu/cu ft	75
Fuel oil	138,000 Btu/gal	65
LP gas	93,000 Btu/gal	90
Electricity	3412 Btu/kwh	100
Hard woods	24 million Btu/cord	50
Coal	25 million Btu/ton	65

Example 18: Find the maximum temperature rise the collector of Ex 17 can produce on Nov. 1.

Answer:

(1) The maximum temperature rise occurs on sunny noons. Lincoln's latitude is about 41°, Fig 41. Use the noon hour, clear day solar radiation for a latitude + 15° surface, Oct. 21, 40° north latitude (closest tabulated date and latitude), Table 23c.
Noon hour, clear day solar radiation = 310 Btu/hr-ft^2

(2) The freestanding collector plan does not give noon collector efficiency. Assume noon efficiency = avg. all day efficiency + 5%.
Noon hour efficiency = 60% + 5% = 65%.

(3) Maximum temperature rise

$$= \frac{\underset{(\text{ft}^2)}{\text{Collector area}} \times \underset{(\text{Btu/hr-ft}^2)}{\text{Noon hour, clear day solar radiation}} \times \text{Noon collector efficiency}}{1.1 \times \text{Collector airflow (cfm)}}$$

$$= \frac{1000 \text{ ft}^2 \times 310 \text{ Btu/hr-ft}^2 \times 0.65}{1.1 \times 6875 \text{ cfm}} = \textbf{about 27F}$$

(Note: The maximum temperature rise for this collector is about 5 times the 24-hour average for the season.)

Example 19: Same as Example 17, but select a collector in the roof and sidewalls of a machine shed. The building is 50' x 100' (oriented east-west) with 14' sidewalls and 4/12 roof slope. Use 50% and 40% for the average all day sidewall and roof collector efficiencies.

Answer:

(1) The average solar energy available on the collector surfaces, Table 23i, appendix:
Btu/day-ft^2:

	Vertical	4/12 Roof Slope
Oct.	1357	1503
Nov.	1220	1058
Avg.	1289	1281

(2) For a 4/12 roof slope, the rafter is about 1.05 times the run:
Roof slope length (ft)
= 1.05 x 1/2 Building width (ft)
= 1.05 x 1/2 x 50ft = 26.25 ft

(3) Q (Btu/day)
= 1.1 x Collector airflow (cfm) x Avg. temp. rise(F) x 24 (hr/day)
= 1.1 x 6875 cfm x 5 F x 24 hr/day
= 907,500 Btu/day

(4) W (Btu/day-ft)
= Daily energy from wall per ft of building length

$$= \underset{(\text{Btu/day-ft}^2)}{\text{Avg. solar energy on wall}} \times \text{Wall efficiency} \times \underset{(\text{ft})}{\text{Wall height}}$$

= 1289 Btu/day-ft^2 x 0.50 x 14 ft
= 9023 Btu/day-ft

(5) R (Btu/day-ft)
= Daily energy from wall per ft of building length

$$= \underset{(\text{Btu/day-ft}^2)}{\text{Avg. solar energy on roof}} \times \text{Roof efficiency} \times \text{Roof slope length (ft)}$$

= 1281 Btu/day-ft^2 x 0.40 x 26.25 ft
= 13,451 Btu/day-ft

(6) Collector length (ft)

$$= \frac{Q}{W+R}$$

$$= \frac{907{,}500 \text{ Btu/day}}{9023 \text{ Btu/day-ft} + 13{,}451 \text{ Btu/day-ft}}$$

= 40.4 ft

If the building trusses are 8' o.c., 5 bays x 8' = 40' long.

(7) Collector area (ft^2)

$$= \left[\text{Wall height (ft)} \times \text{Collector length (ft)}\right] + \left[\text{Roof slope length (ft)} \times \text{Collector length (ft)}\right]$$

= [14' x 40'] + [26.25' x 40']
= 560 ft^2 + 1050 ft^2 = **1610 ft^2**

Note that the collector in Example 19 is larger than in Example 17. Wall and roof solar collectors are each less efficient and have less solar energy (per sq. ft.) available than the freestanding collector at a near-optimum tilt. Still, the total cost for the machine shed collector might be lower than for the freestanding one because of the lower cost per square foot. Calculate the size and cost of each option before choosing one. See Estimating Costs.

Estimating Costs

First Cost

First cost is your investment in the system to collect and use solar energy. Include everything extra that would not be needed without solar: collector, vents, ducts, storage, fans, controls, shutters, stirrer, desiccant grain, labor, etc. Deduct any applicable investment and energy tax credits—check with a tax specialist.

For estimating costs before construction, use plans and specifications and talk to those who have built solar systems. Cost of commercial collectors may be higher than for home-built ones.

Yearly Cost

Yearly cost includes fixed costs (depreciation, interest, property taxes, insurance) and variable costs (repairs and maintenance, any extra electricty required to operate the system).

Yearly Fixed Costs

Most of the components of a solar system should last 10 years, so depreciate the system based on a 10-year life. Because polyethylene covers last only a year, add their replacement cost to the annual repair cost.

Interest can be computed a number of ways—simple interest on the first cost is easy to figure. Real estate and personal property tax information are available locally. Some states exempt solar installations from property taxes. Consult your insurance company about rates—some companies do not insure roof-mounted liquid collectors.

Estimated expenses can be claimed against income for tax purposes, so calculate the tax savings on each expense item. Subtract total tax savings from total expenses to get Net Yearly Fixed Cost.

Yearly Variable Costs

Estimate repairs and maintenance at 2% of first cost. Add the replacement cost for any polyethylene covers. If extra or larger fans were installed to operate the solar system, estimate the extra energy required and the price paid for that energy. Deduct tax savings from the energy cost.

Net Yearly Cost

Add the Net Variable and Fixed Yearly Costs to estimate the annual cost of owning and operating the solar system.

Income

As income against the cost of the solar system, include only the value of useful energy collected. For example, on some sunny spring and fall days, solar collectors on livestock buildings are bypassed to avoid overheating. And, energy is collected only part of the year for building heating or grain drying. Estimate the number of days per year that the collector will provide useful energy. Using the average solar energy available in your area (Table 23), calculate the collector's annual energy production:

$$\begin{gathered}\text{Yearly solar energy (Btu/yr)} = \text{Collector area (ft}^2\text{)} \times \text{Average energy available (Btu/day-ft}^2\text{)} \\ \times \text{Average all day efficiency} \times \text{Annual use (days/yr)}\end{gathered}$$

The value of solar energy depends on the type and price of the fuel being replaced. Use heating values from Table 21.

$$\text{Fuel value (\$/Btu)} = \frac{\text{Fuel price (\$/unit)}}{\text{Heating value (Btu/unit)}} \times \text{Heater efficiency}$$

$$\text{Solar income (\$/yr)} = \text{Yearly solar energy (Btu/yr)} \times \text{Fuel value (\$/Btu)}$$

Although the cost of solar energy now often exceeds solar income, changing fuel costs and improving technology may change this relationship.

Beware of cost estimates based on building heat balances or water removed from drying grain. Natural air contains heat—enough to dry grain with proper management—which cannot be credited to the solar collector.

First Cost

1. Materials ______
2. Additional equipment (Ducts, controls, shutters, etc.) + ______
3. Labor + ______
4. Total construction cost = ______
5. Less tax credits – ______
6. First Cost: = ______

Yearly Fixed Costs

Expenses

7. Depreciation ______
8. Interest on First Cost + ______
9. Property taxes, if any + ______
10. Insurance + ______
11. Total Expenses = ______

Tax Savings:

12. Depreciation ______
13. Interest + ______
14. Property tax + ______
15. Insurance + ______
16. Total Savings = ______
17. Yearly Fixed Cost (11-16) = ______

Yearly Variable Costs

Expenses:

18. Repairs and maintenance ______
19. Energy to operate, if any + ______
20. Total Expenses = ______

Tax Savings:

21. Repairs and maintenance ______
22. Energy expenses + ______
23. Total Savings = ______
24. Yearly Variable Costs (20-23) = ______
25. Total Net Yearly Cost (17+24) = ______

Income

26. Yearly Solar Energy ______ Btu/yr
27. Value of fuel replaced x ______ $/Btu
28. Solar Income = ______ $/yr

SOLAR COLLECTOR PLANS

The solar collectors in this section are examples of ones suitable for grain drying and do-it-yourself construction. Select one without heat storage for grain drying only. For multiple use, consider relative positions of your buildings, and plan new units to avoid long ducts.

Although the optimum tilt angle for fall grain drying is latitude + 15°, cost, convenience, or multiple-use may dictate some other angle. Efficiency is affected by materials, weather, airflow, etc. A rough estimate of average all day efficiency is noted on each plan—add 5% for the noon hour efficiency on sunny days.

Your efficiency will probably be reduced if airflow per unit surface area (cfm/ft^2) is much lower than the rate specified on some of the plans. Maintain air velocity at 500 to 1000 fpm past the absorber (probably not possible in solar attics which have large cross-sectional areas). And, limit total pressure drop to 1/2" for grain drying and 1/8" for building ventilation.

See the section on collector materials before starting construction. Consider flat as well as corrugated covers. Make them raintight by sealing laps and edges. Put screws on corrugation ridges on slopes below 40° (10/12 slope); on walls or steeper slopes, they can go in the valleys. With FRP covers, a collector can be expected to last 10 years.

Insulate collectors and ducts to R = 6 except for low temperature applications like grain drying.

Make air ducts large (at least 1 ft^2/1000 cfm) and as streamlined, airtight, and short as possible.

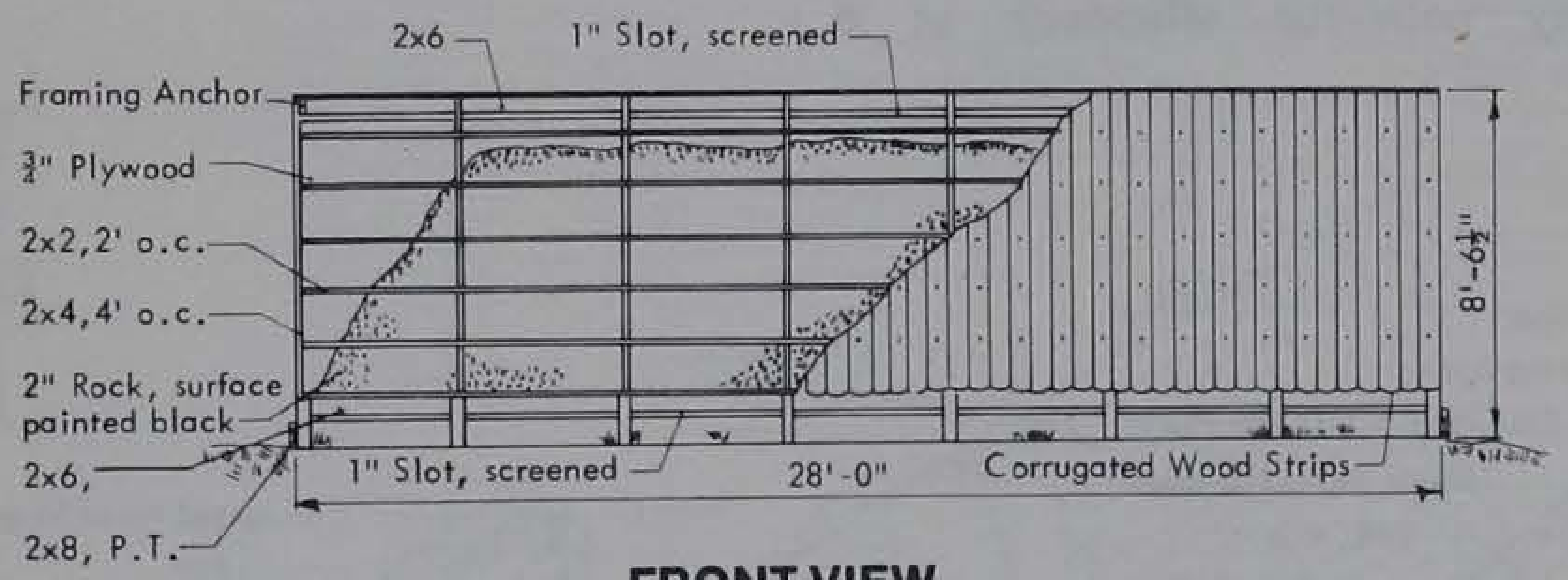
Collector with Rock Pile Heat Storage

This unit combines the collector and heat storage. Black-painted 2" diameter rocks are the absorber and the storage. Air is pulled across the surface of the pile, down through the rocks, and into a perforated duct by the drying or ventilating fan. The solar heat is temporarily stored in the rock pile—air leaving the rock pile is warmest in the evening and coolest in the morning.

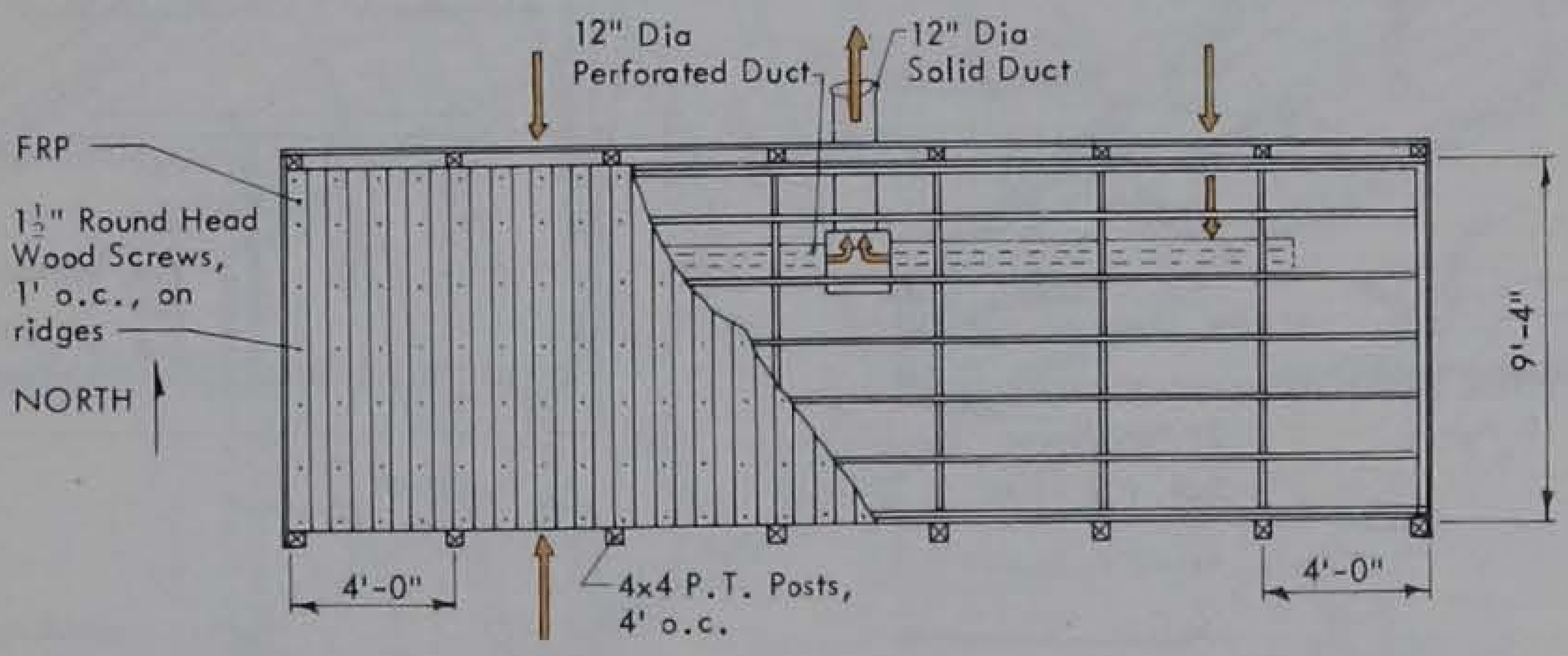
The time lag in air temperature is beneficial for preheating ventilating air for livestock buildings, but it is really not necessary for drying grain. Because the collector-storage unit is more expensive than a simple flat plate collector and you don't need storage for grain drying, don't build this unit for only grain drying. For both space heating and grain drying, locate the grain bin near the building because the unit is not portable.

Construction steps:

1. Set the posts and build the lumber framework—install every other rafter.



FRONT VIEW



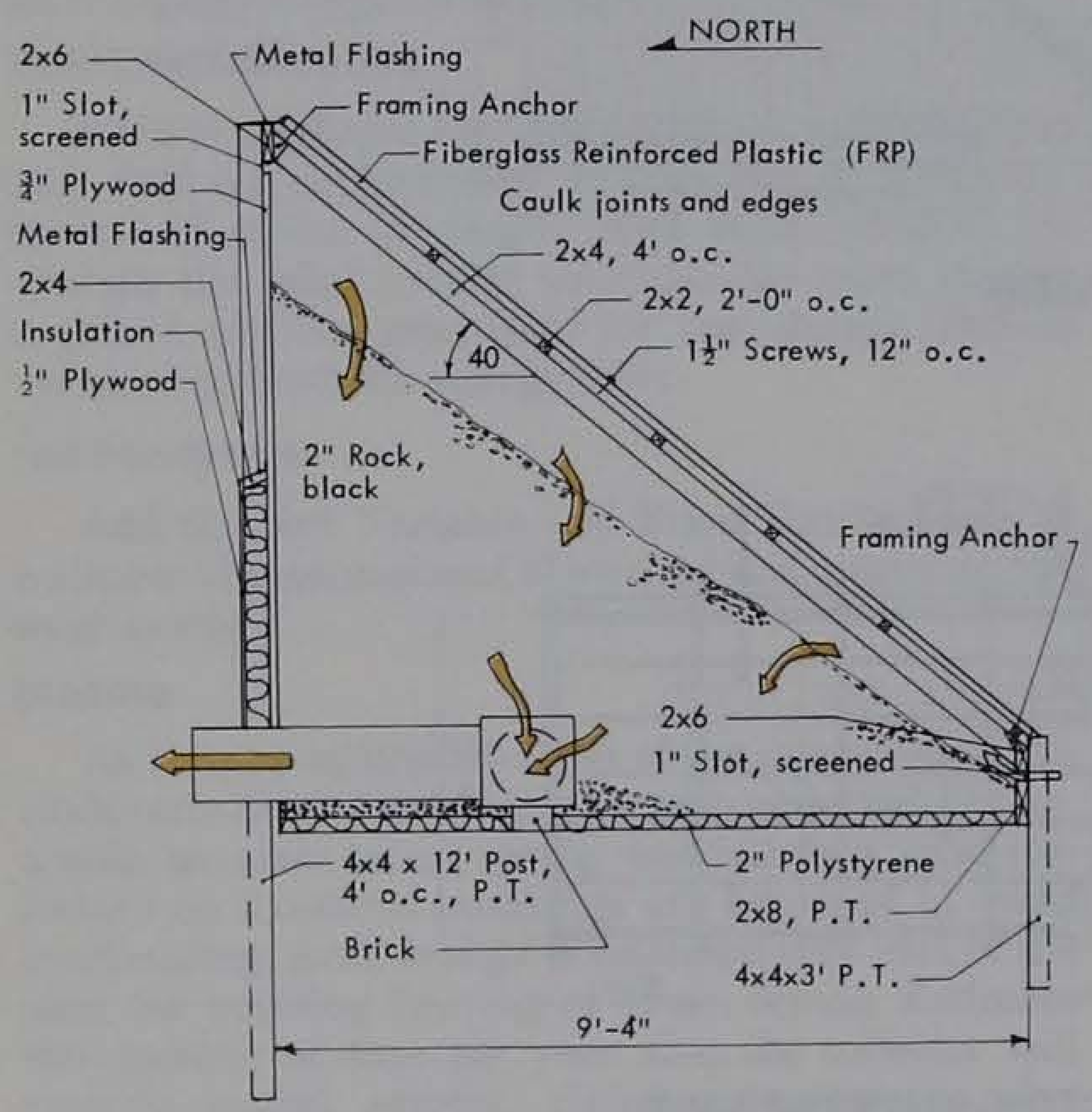
TOP VIEW OF COLLECTOR-STORAGE UNIT

2. Install the loosefill insulation between the north posts and place the rigid polystyrene on the ground.
3. Set the air ducts on bricks or blocks. (Cut holes in the polystyrene.)
4. Carefully pile the rocks over the ducts and as far up the back wall as possible.
5. Spray the rock pile and exposed plywood with flat black paint.
6. Install the other rafters.
7. Install framing on each end.
8. Install fiberglass flush with door openings; run corrugations vertically; seal with corrugated filler strips.
9. Build door frames as shown and install.
10. Cover door frames with 40" section of fiberglass; extend 1½" past bottom of frame and match corrugations with those on the wall.
11. Attach the roof cover material. Caulk sheet laps and edges to keep water out of the collector.

The cover tilt angle is only 40°—flatter than the latitude + 15° recommended in the North Central Region. A steeper angle increases the amount of lumber and cover material required, but does not greatly increase the amount of energy collected. And 2" rock piles no steeper than about 35°.

Use rock with uniform diameters and smooth surfaces because rough, poorly graded rock causes high pressure drops. If possible, use local rock to minimize transportation costs.

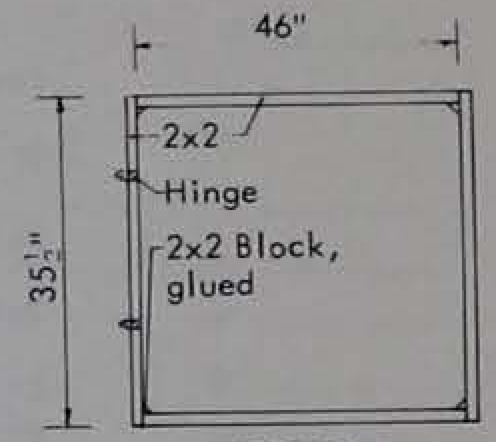
Average all-day collector efficiency at 6 cfm/ft^2 = 45%.



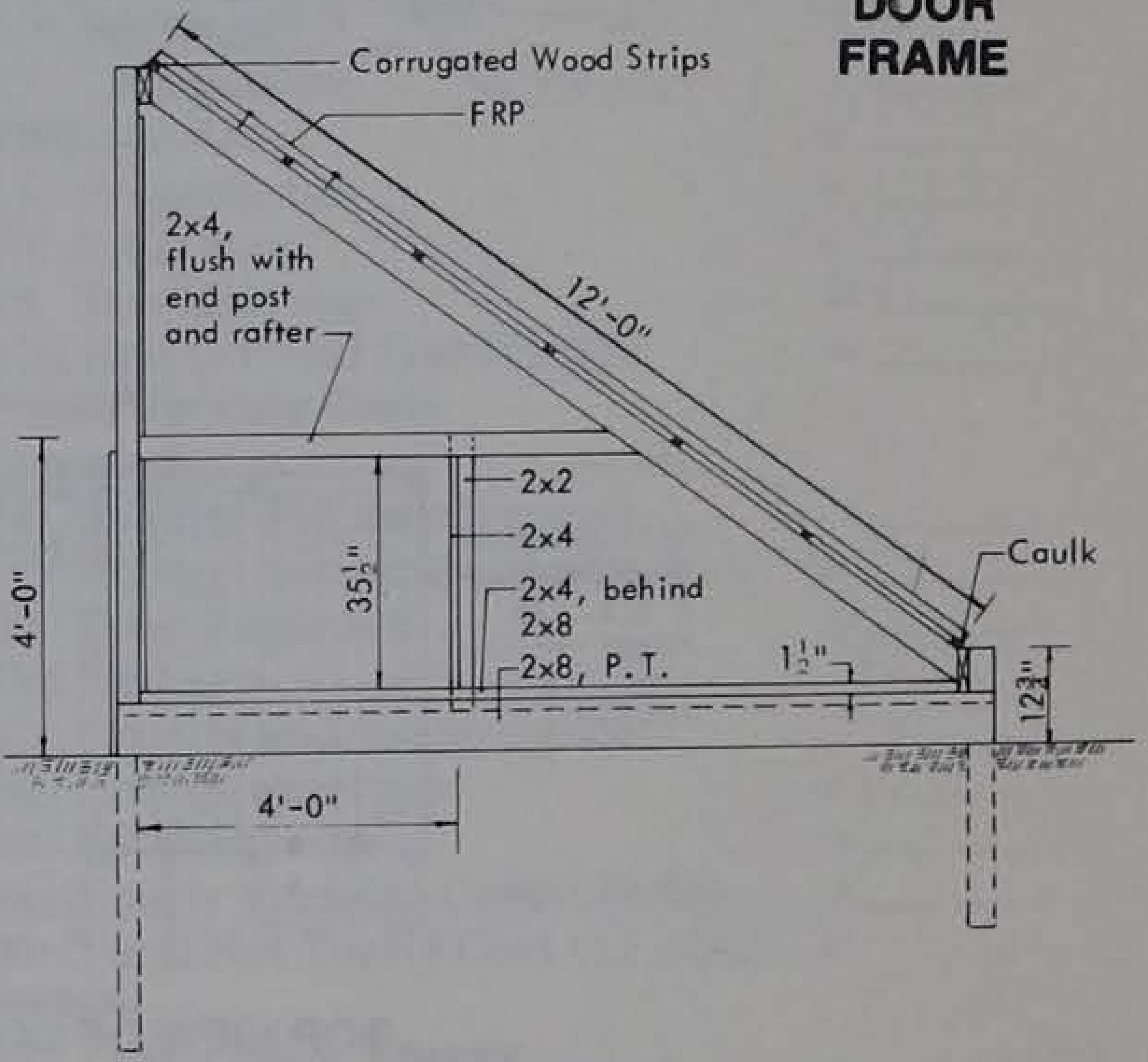
SECTION THROUGH AIR OUTLET DUCT

BILL OF MATERIALS

Quantity	Description
8	4x4 x 12' P.T.
8	4x4 x 3' P.T.
1	2x8 x 12' P.T.
1	2x8 x 16' P.T.
2	2x8 x 10' P.T.
2	2x6 x 16'
2	2x6 x 12'
10	2x4 x 14'
4	2x4 x 10'
22	2x2 x 12'
7	4'x8'x ¾" Ext. Plywood
4	4'x8' x ½" Ext. Plywood
7	4'x12' FRP
37 cu ft	Loose Fill Insulation
2	4"x28' ¼" Hardware Cloth
70'	Corrugated Filler Strips
14	4"x4' Flashing
16 gal	Flat Black Paint
32 tons	2" Rock
2	12" dia x 10' Perforated Ducts
2	12" dia Perforated End Caps
1	T-Duct Section for 12" dia Duct
1	12" dia Solid Duct, as needed
4	Small Door Hinges
2	Door Latches
25	Bricks
5 lb	#20 Common Nails
1 lb	#6 Common Nails
16	Framing Anchors
250	#8, 1½" Round Head Wood Screws.



DOOR FRAME



END VIEW

Portable Collectors

A stationary solar collector usually requires a long, inefficient duct to provide heat for more than one application. But, you can move a portable collector from use to use during the year. By increasing the total amount of energy collected over its life, the collector is more apt to pay for itself. Collectors developed at the University of Illinois and at Purdue are illustrated.

University of Illinois Portable Collector

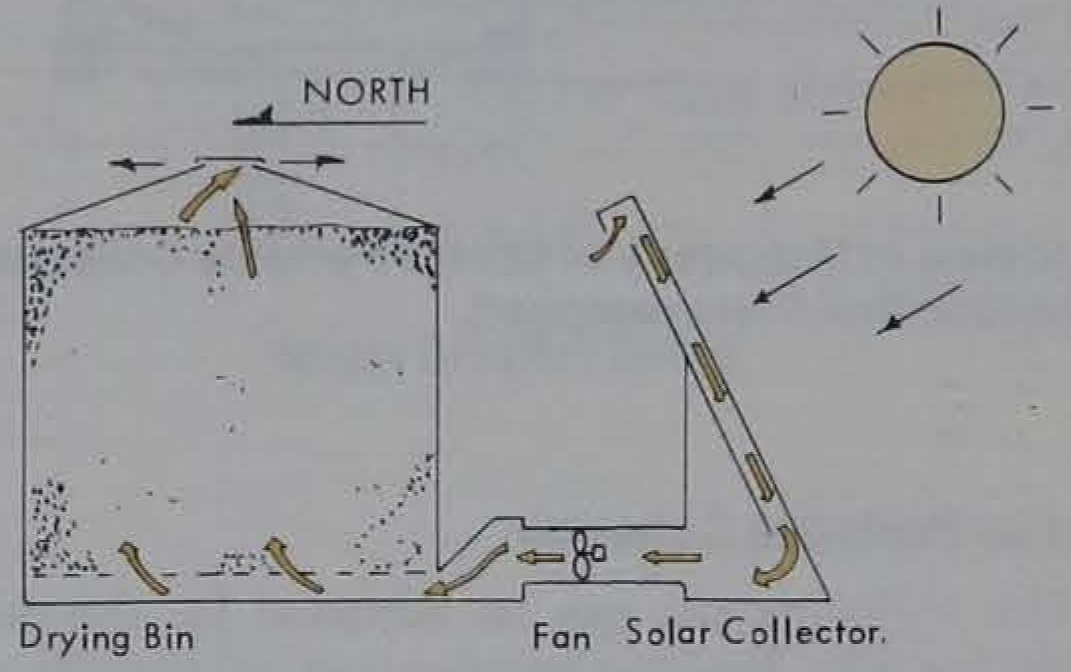
This collector is for a small temperature rise for grain drying. The 63° tilt angle gives maximum energy for fall grain drying in northern Illinois, but should be satisfactory for drying grain or heating livestock buildings anywhere in the North Central Region. If you plan to preheat livestock building ventilating air, insulate the floor, end walls, and back wall of the collector plenum and the air duct to about R=6. (See Insulation.)

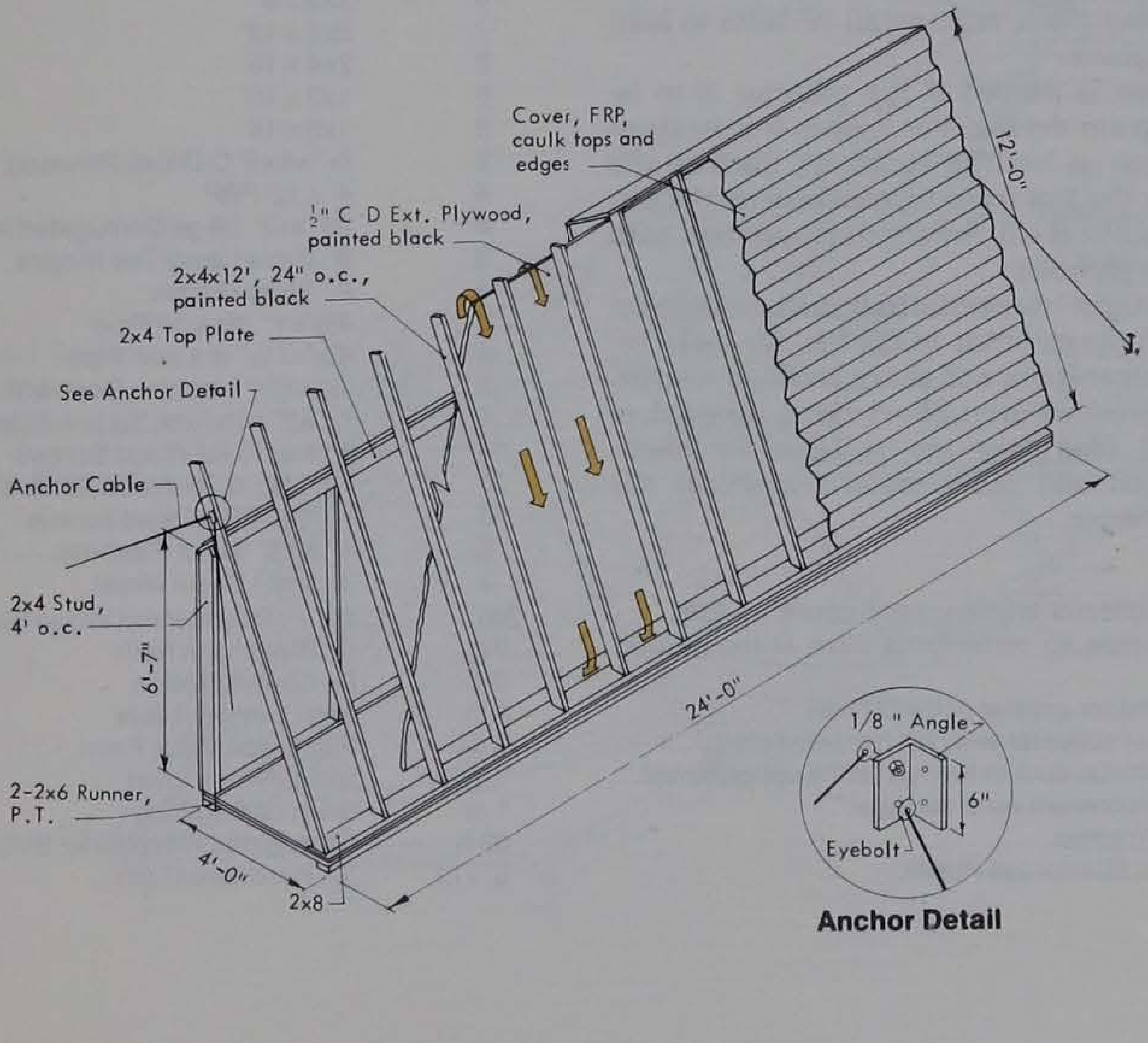
BILL OF MATERIALS

One 12' x 24' Collector

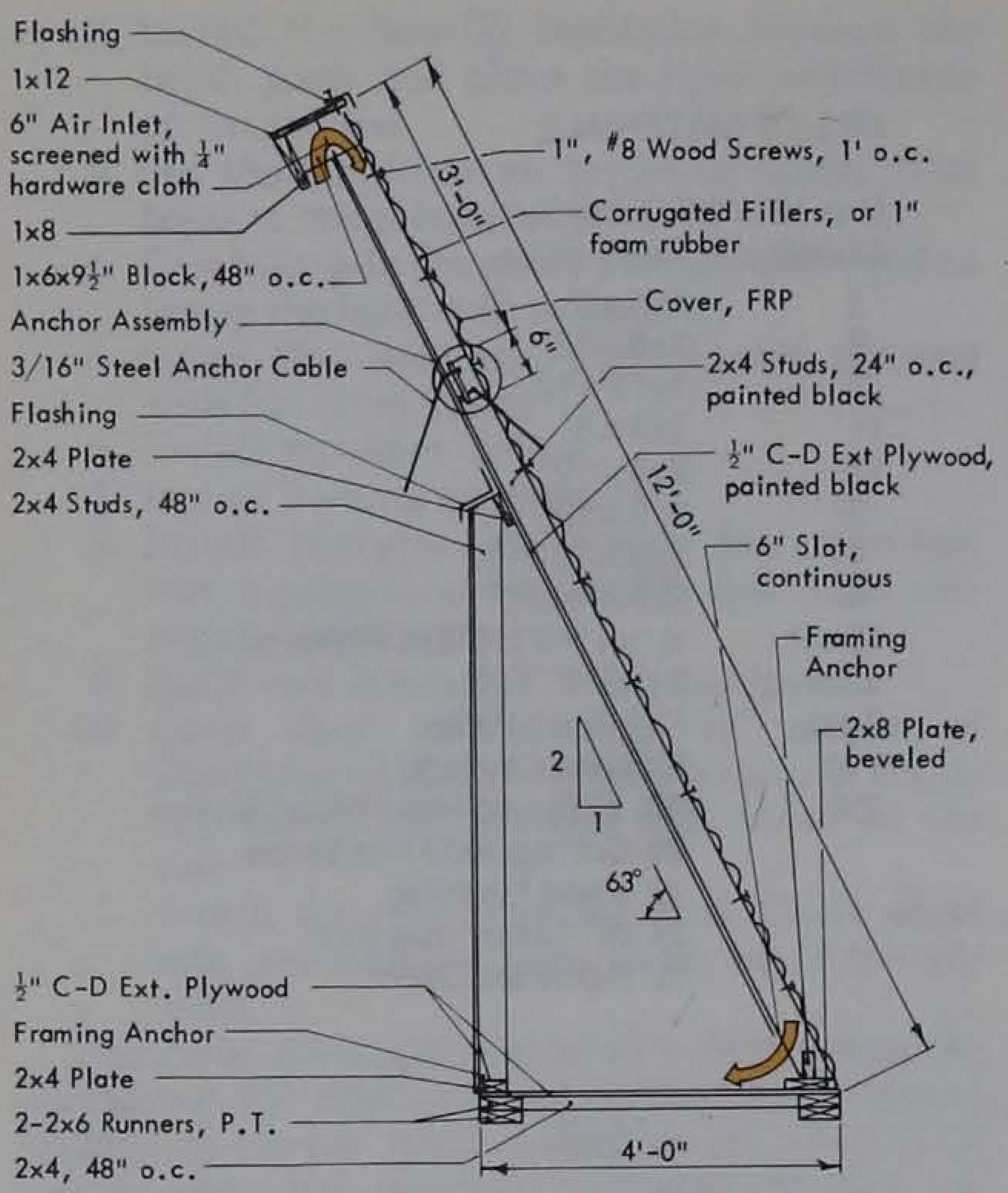
Quantity	Description
1	1x6 x 6'
2	1x8 x 12'
2	1x12 x 12'
11	2x4 x 8'
17	2x4 x 12'
2	2x8 x 12'
4	2x6 x 10' P.T.
4	2x6 x 14' P.T.
19 sht	1/2"x4' x 8' C-D Ext. Plywood
5 sht	24'x2'-6" FRP
2 gal	Flat Black Paint
1 qt	Silicone Caulking
250	#8, 1" Round Head Wood Screws
	25' Corrugated Filler Strips
	72' Metal Flashing
	24'x8" Gutter Guard or
	1/4" Hardware Cloth

Average full-day collector efficiency @ 15 cfm/ft^2 = 70%.
Cover ends of the collector with plywood.
Duct heated air through opening in end or back of collector.
Make opening same size as drying fan or larger.
Anchor securely against wind damage.
P.T. = Pressure Treated.
FRP = Fiberglass Reinforced Plastic.





Anchor Detail



Endview of University of Illinois Portable Collector. Plywood End Plate removed.

Purdue Portable Collector

The collector tilt can be adjusted for the proper angle for any heating application at any location. Just raise the collector to the desired angle, drill holes in the telescoping pipes, and install ¼" bolts to hold the collector in place.

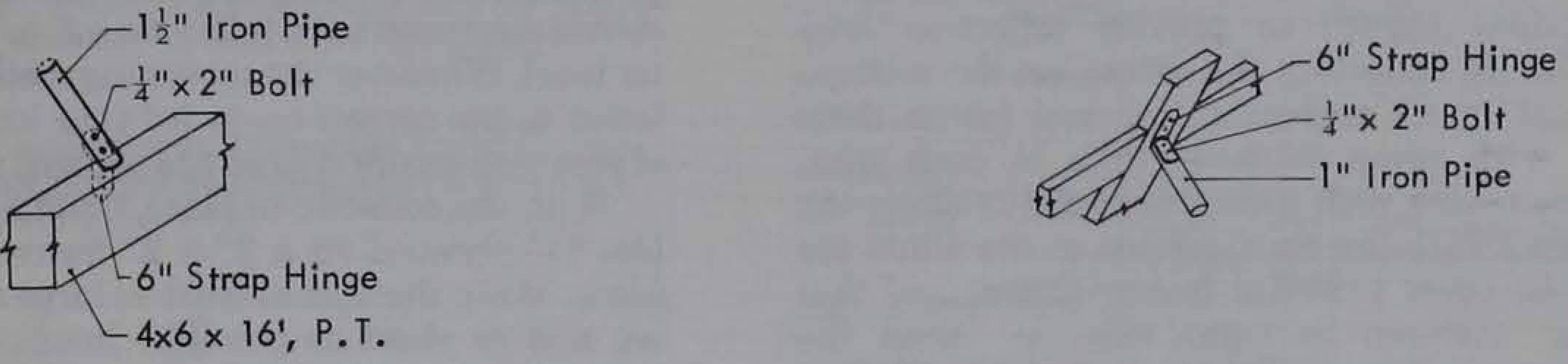
No insulation is needed if the collector is to be used only for grain drying. For higher temperature applications such as heating buildings, insulate the spaces between the 2x4 framing members on the collector back to about R=6. Secure the insulation with wood battens or plywood.

Build an airtight, streamlined transition to direct heated air from the collector to the fan. Air leaks reduce the air temperature, and sharp bends or obstructions increase pressure drop. Sheet metal, plywood, or rigid foil-faced fiberglass are suitable for ducts. Insulate plywood and sheet metal transitions the same as the collector.

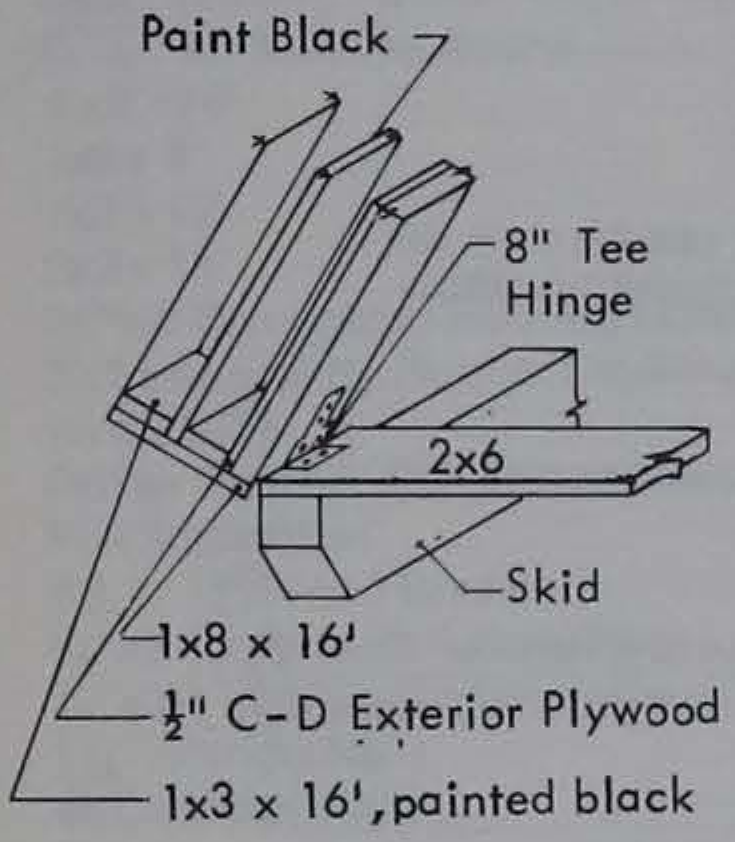
Average full-day collector efficiency @ 5 cfm/ft² = 50%.
Drill holes in 1" pipe so collector is tilted at the desired angle.
Set units end to end for greater collector area.
Cover intake end of collector with ¼" hardware cloth.
Build plywood or metal duct to the fan on the opposite end.
Anchor securely to prevent wind damage.
P.T. = Pressure Treated.
FRP = Fiberglass Reinforced Plastic.

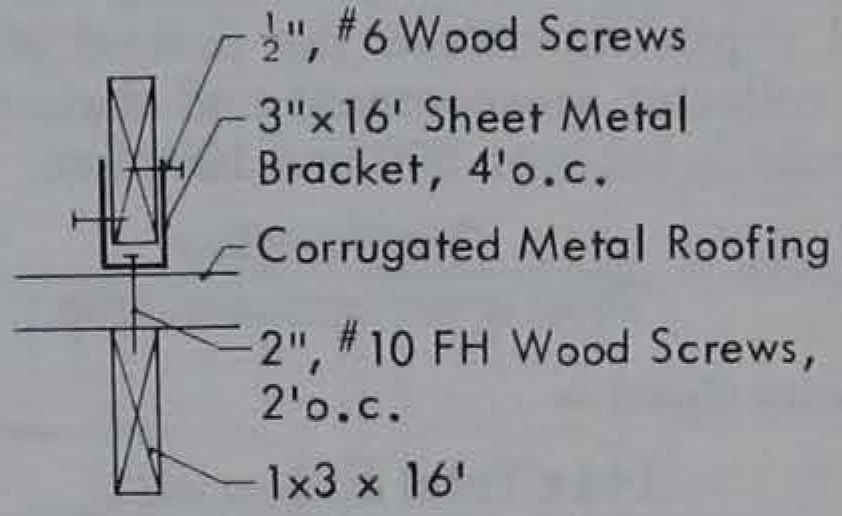
BILL OF MATERIALS
One 12' x 16' Collector

Quantity	Description
2	4x6 x 16' P.T.
3	2x6 x 8'
7	2x4 x 12'
2	2x4 x 16'
8	1x3 x 16'
2	1x8 x 16'
6	½"x4 x 8' C-D Ext. Plywood
4	4' x 12' FRP
8	26"x12', 28 ga Corrugated Metal Roofing
3	8" Extra Heavy Tee Hinges
4	6" Strap Hinges
2	4½'x1" dia Iron Pipe
2	4½'x1½" dia Iron Pipe
8	¼"x2½" Machine Bolts with Nuts
4	¼"x2" Machine Bolts with Nuts
18	2" No. 10 FH Wood Screws
30	1½" No. 6 RH Wood Screws
60	½" No. 6 Pan Head Screws
2	4" x 16' Metal Flashing
2	3" x 16' Sheet Metal
200	#8, 1" Round Head Wood Screws
2 lb	6d Ringshank Nails
2 lb	8d Common Nails
2 lb	16d Common Nails
1 gal	Flat Black Metal Paint
½ gal	Metal Primer Paint
1 qt	Silicone Caulking
32 ft	Corrugated Wood Filler Strips
8"x12'	¼" Hardware Cloth

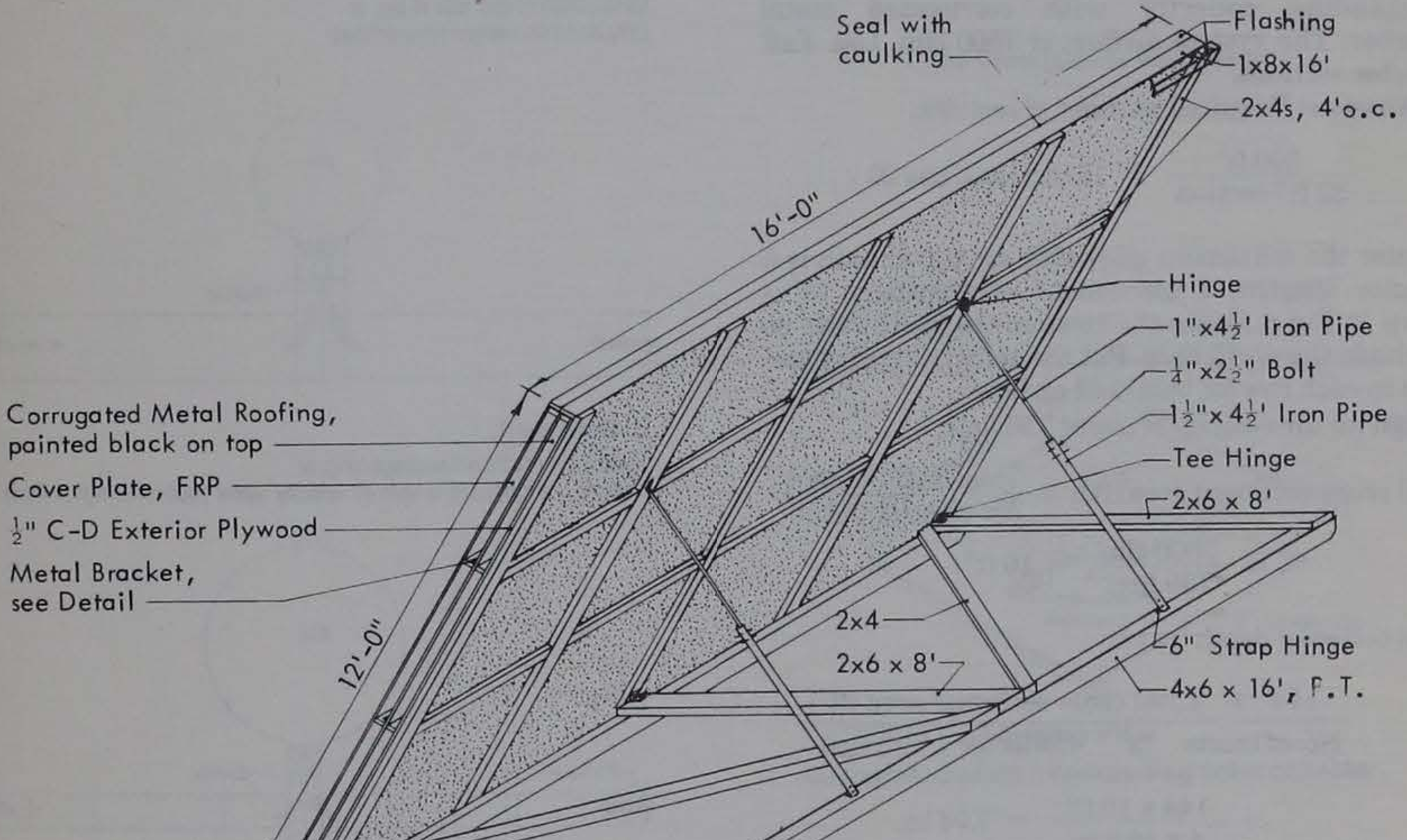


Hinge Details





Metal Bracket Detail



Freestanding Collectors

The two collectors illustrated were developed and tested at the USDA lab at Ames, IA. Build enough 4' x 8' sections (32-ft^2) to provide collection area needed. Before installing the covers, set the sections end to end in an east-west line and fasten them together with seven ¼" x 4" bolts at each joint. Install the covers with generous caulking along the edges. Make sure the corrugations at the joints are lined up (if cover material is corrugated) and that the cover material is right side up. (Read the manufacturer's literature.) Cut 4" wide strips of cover material to seal the joints.

Several arrangements of the collector sections are possible. Long collectors are inefficient, so split the collector if more than 6 sections are needed. Collector arrangement also determines the number of air inlets and can be used (along with collector channel depth) to obtain the desired air velocity. Choose collector arrangement and channel depth so air velocity is between 500 and 1000 fpm.

$$\text{Air velocity} = \frac{\text{Total airflow}}{\text{Total cross-sectional area}}$$

$$\text{Air velocity (fpm)} = \frac{144 \times \text{Total airflow (cfm)}}{\text{No. of inlets} \times \text{Total collector depth (in)} \times \text{Collector width (in)}}$$

Example: Select a 600-ft^2 suspended-plate freestanding collector with corrugated metal absorber. The system airflow is 7500 cfm. Use 4'x8' collector sections.

Answer: Required number of sections:

$$\frac{600\ \text{ft}^2}{32\ \text{ft}^2/\text{section}} = 19 \text{ sections; use } 20$$

Because the maximum allowable air travel path is 6 collector lengths, a convenient arrangement is as shown in Fig d. Space the rows so the south rows do not shade the north ones. Put the same number of sections in each row for balanced airflow.

Design for air velocity of about 750 fpm:

$$\text{Total cross-sectional area (ft}^2\text{)} = \frac{\text{Total airflow (cfm)}}{\text{Air velocity (fpm)}}$$

$$= \frac{7500\ \text{cfm}}{750\ \text{fpm}} = 10\ \text{ft}^2$$

$$\text{Total collector depth (in)} = \frac{144 \times \text{Total cross-sectional area (ft}^2\text{)}}{\text{No. of inlets} \times \text{Collector width (in)}}$$

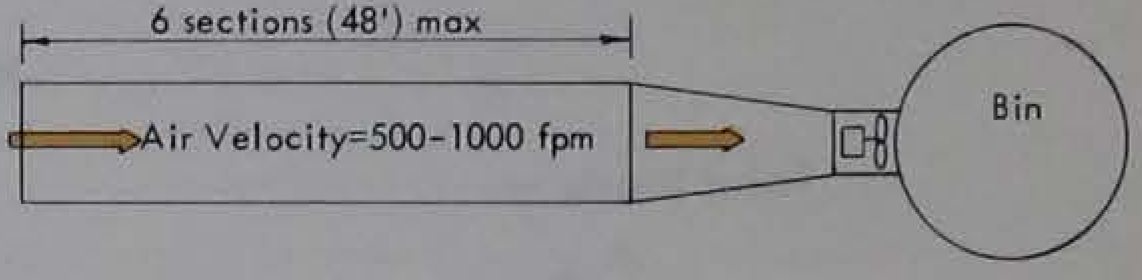
$$= \frac{144 \times 10\ \text{ft}^2}{4 \times 46.5\ \text{in.}} = 7.74\ \text{in.}$$

$$\text{Channel depth} = \tfrac{1}{2} \times \text{Total collector depth} = \tfrac{1}{2} \times 7.74\ \text{in.} = 3.87\ \text{in.}$$

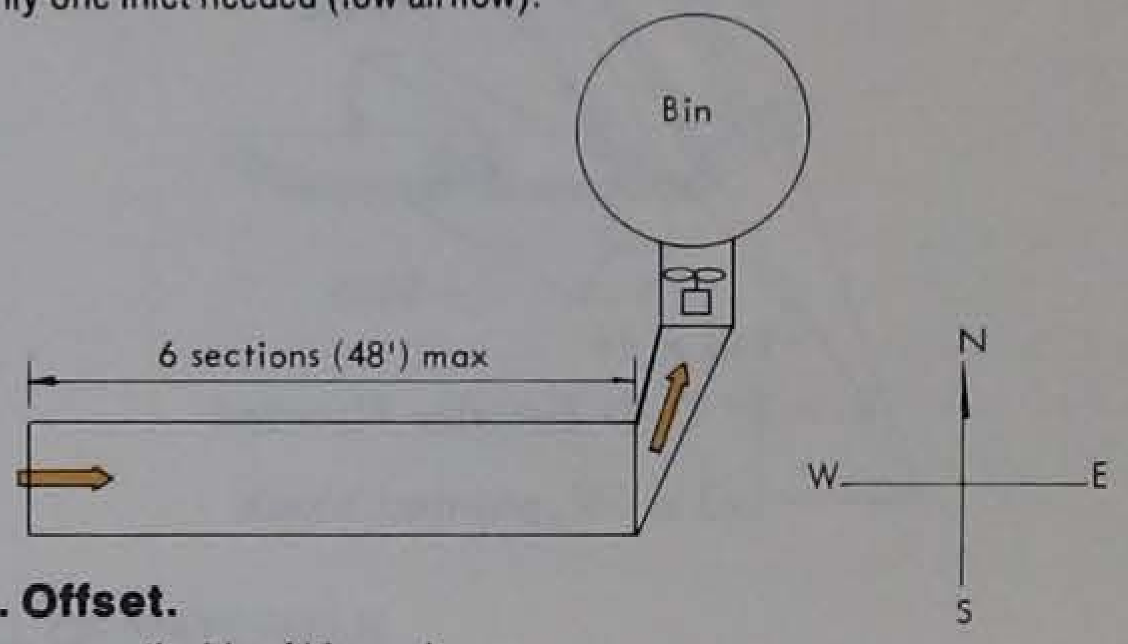
Use **1x4s** as the collector sideplates.

Mount the collector sections on a roof, skids, or stands like those illustrated. On uneven ground, some stands may need to be taller than 6' to keep the collector level. Whatever the mounting method, tilt the collector to the correct angle for your location and time of year and secure it firmly to prevent wind damage.

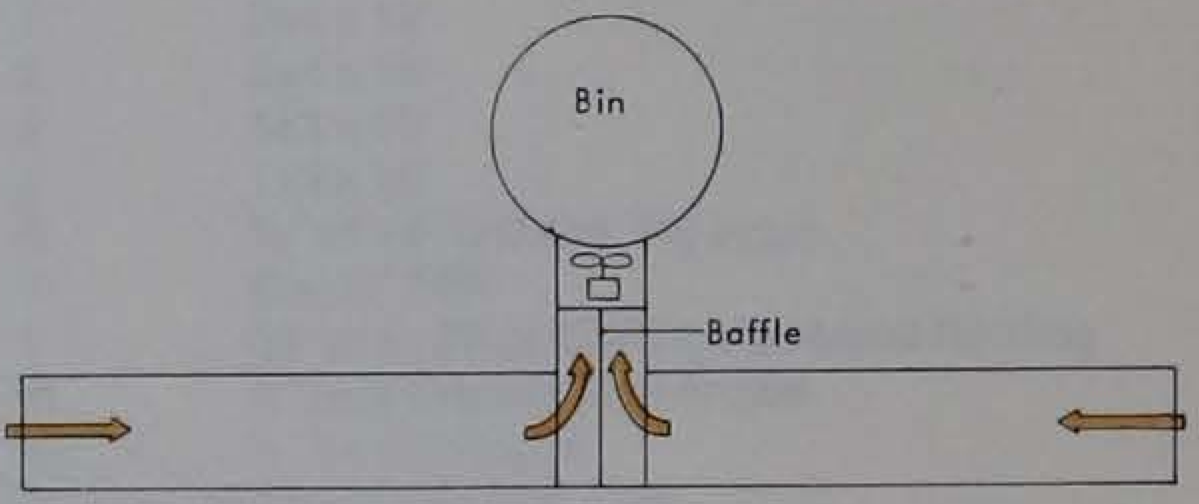
With the collector in place, build a duct to the fan. Use ⅜" plywood on a 2" x 2" frame and caulk the joints. Make the duct at least as large as the fan opening and as short as possible. Insulate the duct the same as the collector.



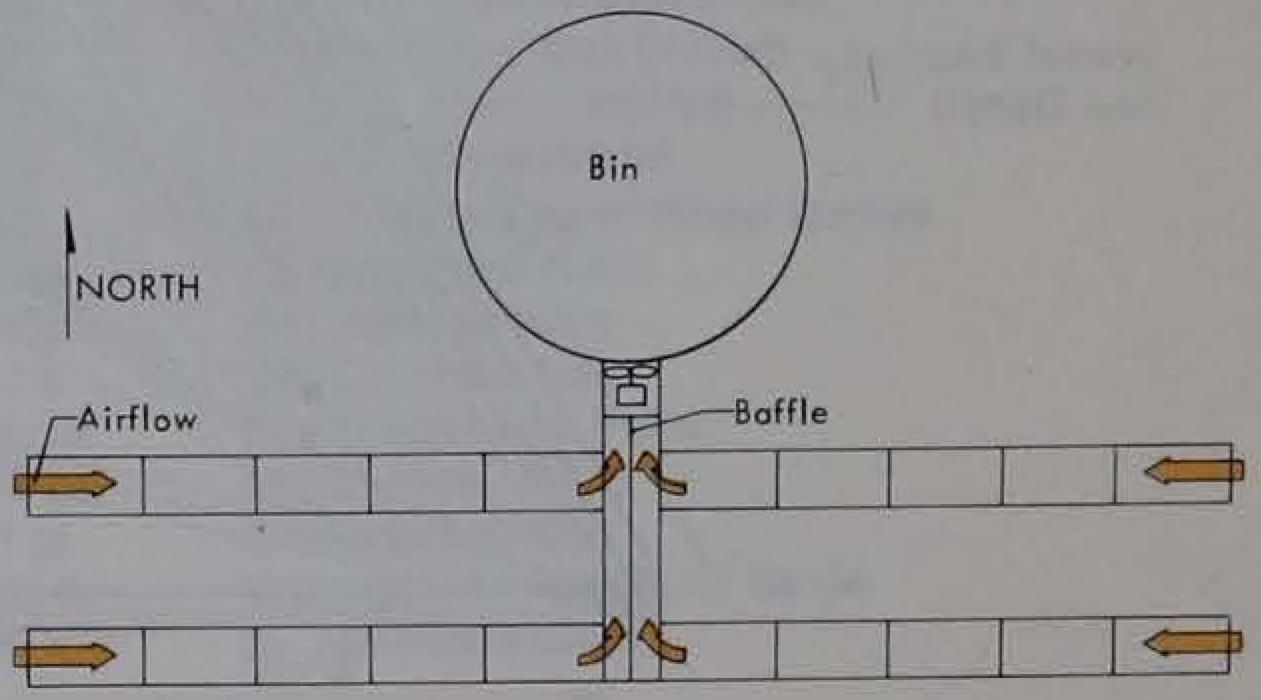
a. In-line.
Fan on east or west side of bin, and
Only one inlet needed (low airflow).



b. Offset.
Fan on south side of bin, and
Obstruction to one side of bin, or
Only one inlet needed (low airflow).



c. Split duct.
Collector more than 6 sections long, or
Multiple inlets needed to keep air velocity below 1000 fpm (high airflow).



d. 20-collector layout.

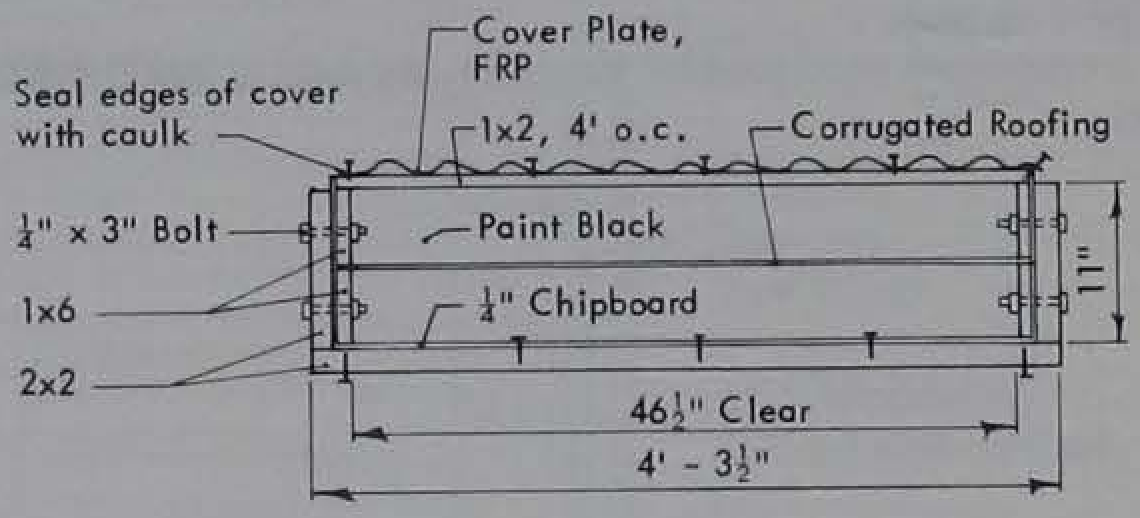
Corrugated-Absorber Collector

Average full-day collector efficiency @ 23 cfm/ft² = 60%.
1x6 sideplates can be replaced with other sizes to change cross-sectional area and air velocity through the collector at a given airflow. Make both channels the same depth. Min. recommended depth is 1½" (2x2s); max. is 11¼" (1x12s).
Glue-nail chipboard to 2x2s and 1x6s.
Build as many units as necessary for your heating needs. See Collector Sizing.
If collector is for livestock building or shop heating, insulate to about R = 6.
FRP = fiberglass-reinforced plastic.

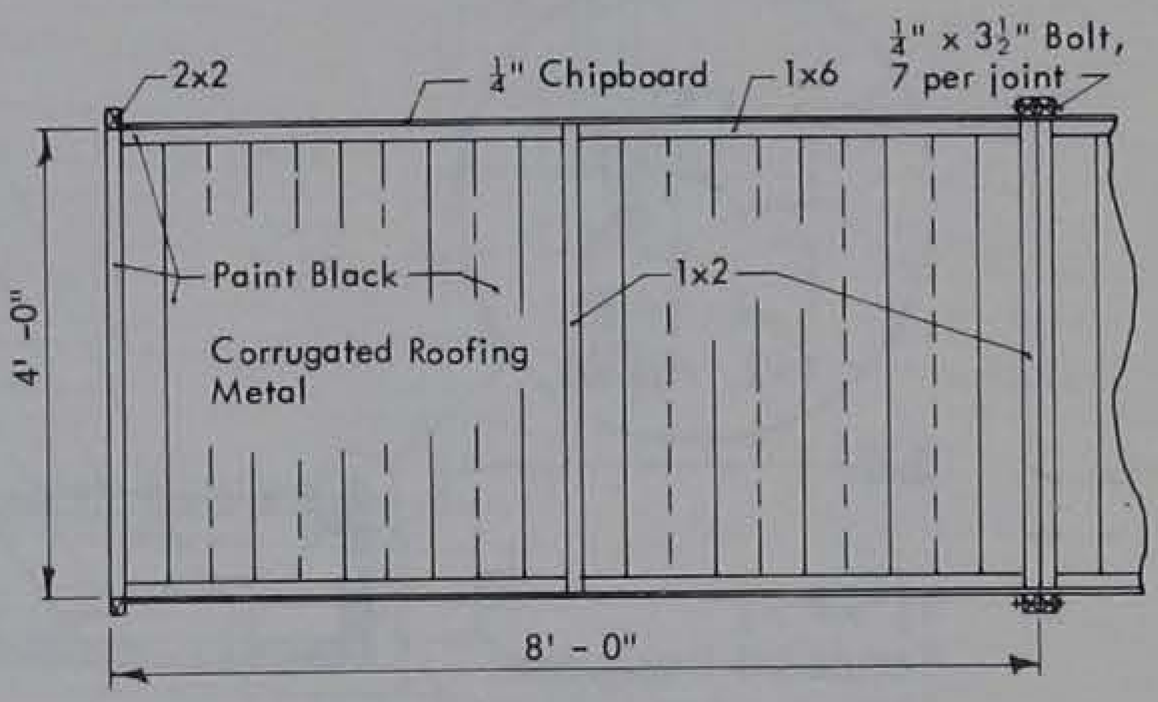
BILL OF MATERIALS—Corrugated-absorber collector.

One 4' x 8' Section.

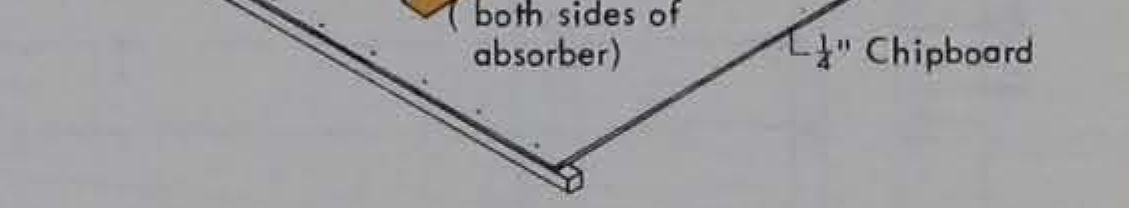
Quantity	Description
1½ shts	¼"x4' x 8' Ext. Chipboard
1 sht	4'x8' FRP
4	1x6 x 8'
1	1x2 x 12'
1	2x2 x 14'
4	26"x4' Corrugated Roofing Metal
½ qt	Silicone or Butyl Rubber Caulking
½ qt	Wood Glue
½ qt	Primer Paint for Galvanized Metal
½ gal	Flat Black Paint
30	#8, 1" RH Wood Screws
8	¼"x3" Bolts (with flat washers)
7	¼"x3½" Bolts (with flat washers)
2 lb	1¼" Shingle Nails
½ lb	#6 Common Nails



End View



Top View (Cover Removed)



Cut-away View

Suspended-plate freestanding solar collector.

Crimped-Absorber Collector

Average full-day collector efficiency = 75% (when air is not recirculated).

This is a multi-use collector, usually too costly for grain drying.

For shop heat, block off upper air channels so air passes only below the absorber. (Low air volume for shop heating needs smaller channel area to keep air speed in the most effective range.)

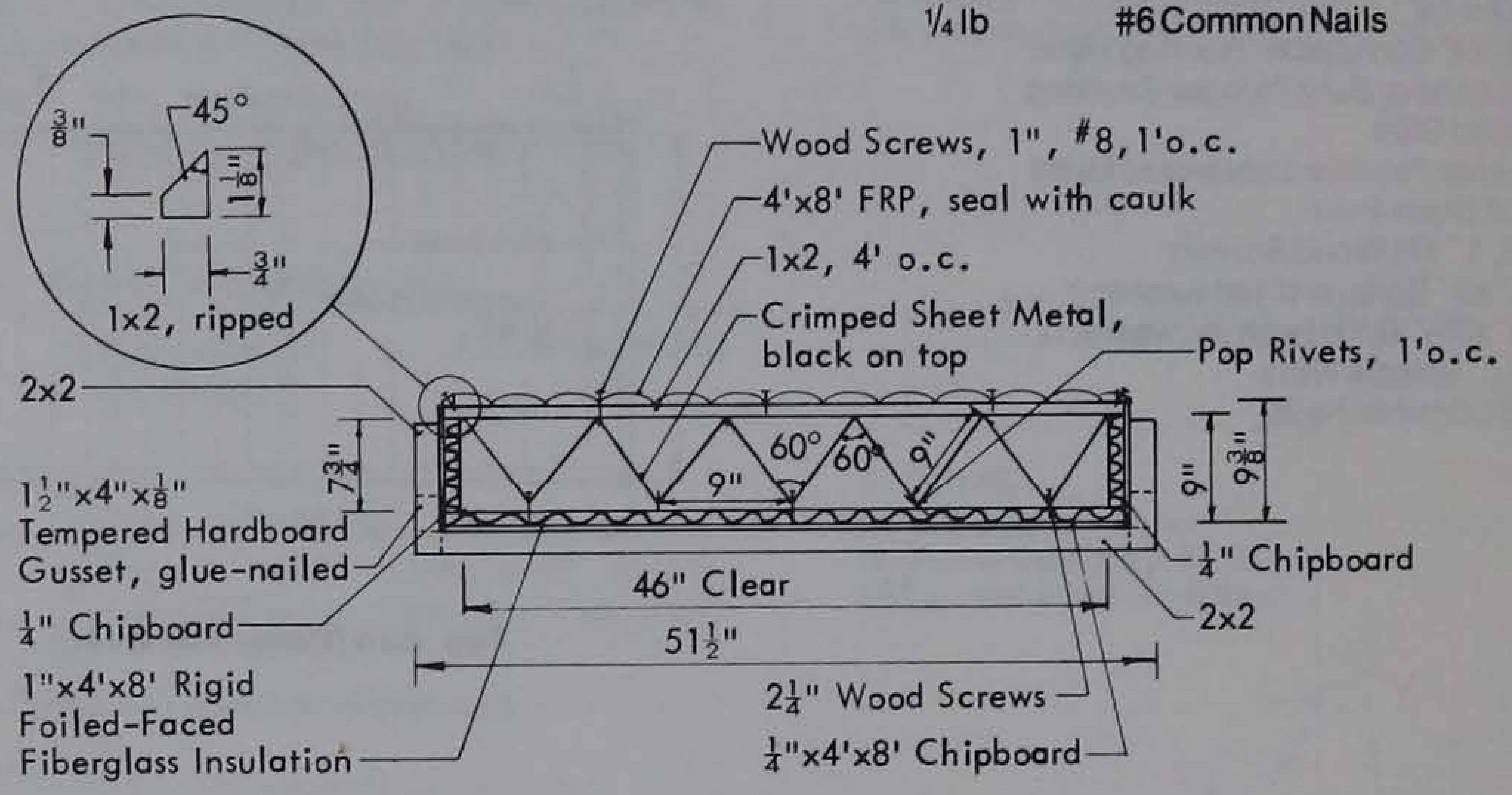
After bending the sheet metal sections, fasten them together with pop rivets 1' o.c.; paint top black.

If air is recirculated, make collector, transitions, and ducts air tight to limit heat losses.

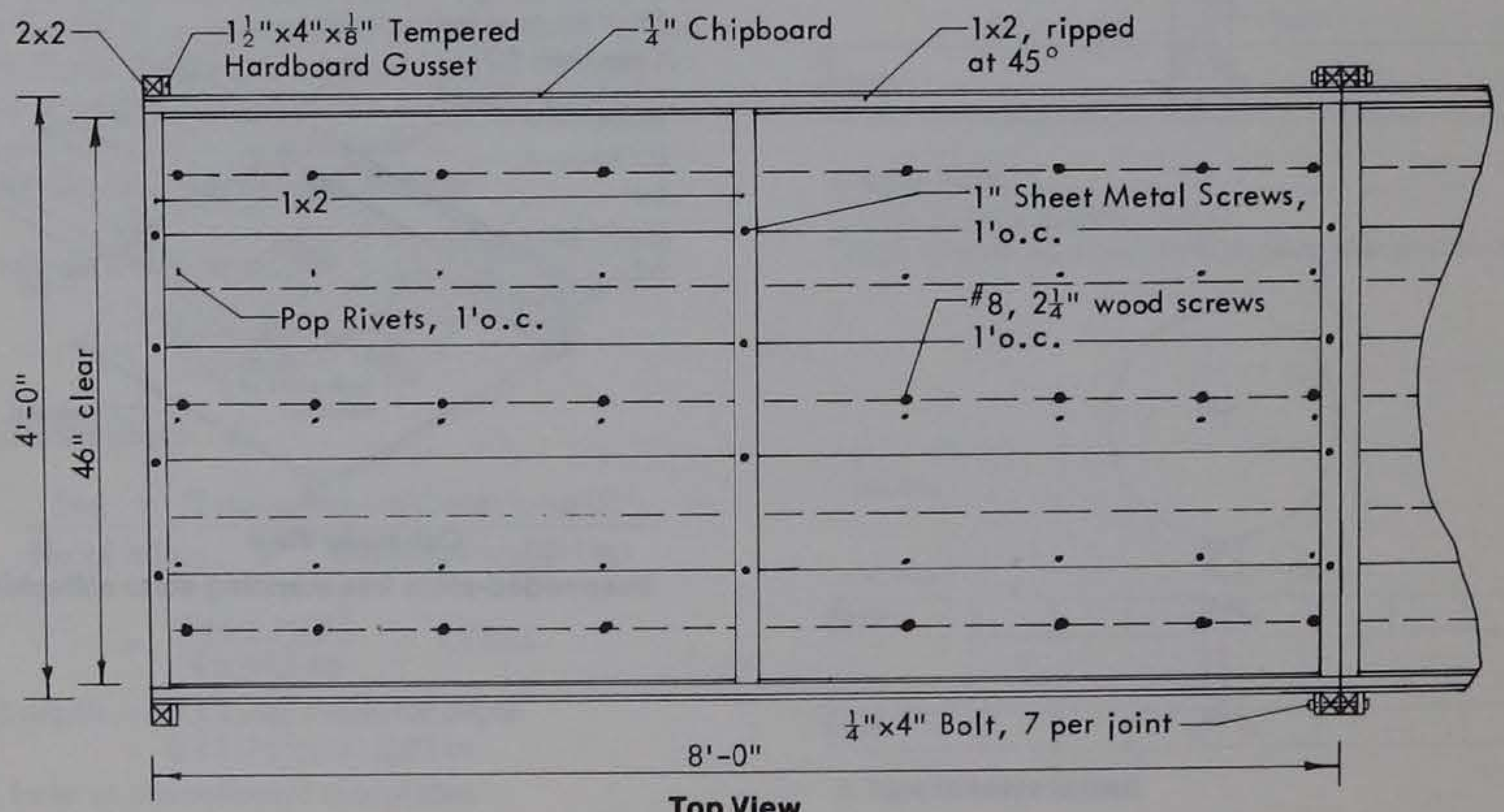
BILL OF MATERIALS—Crimped-absorber collector.

One 4' x 8' Section

Quantity	Description
1½ sht	¼"x4' x 8' Ext. Chipboard
1 sht	4'x8' FRP
1⅓ sht	1"x4' x 8' Rigid Foil-faced Fiberglass Insul.
4 sht	2'x8' 28 ga Sheet Metal
1	1x2 x 8'
1	1x2 x 12'
1	2x2 x 12'
1 qt	Caulk (silicone or butyl rubber)
¼ qt	Glue
⅓ qt	Adhesive for Insulation
½ gal	Flat Black Enamel Paint
½ qt	Primer for Sheet Metal
30	#8, 1" Round Head Wood Screws
7	¼"x4" Bolts (with flat washers)
12	1" Sheet Metal Screws
6	2¼" Wood Screws
⅓ lb	1¼" Plaster Board Nails
¼ lb	#6 Common Nails



End View



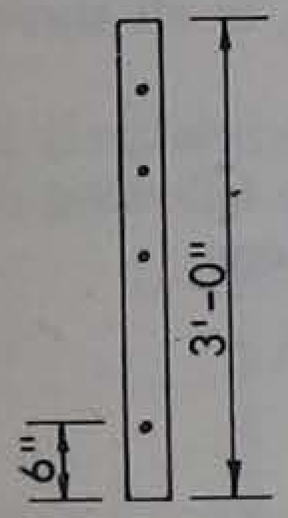
Top View

Adjustable Solar Collector Support Stand

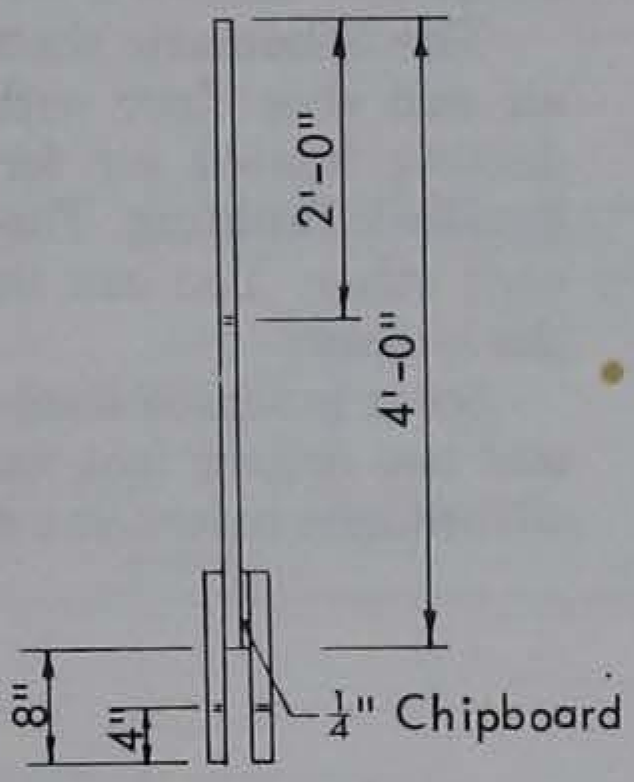
Center one stand under each collector section.

Set the stands at least 2' into the earth; on uneven ground, some legs may need to be longer than 6' to make the collector level.

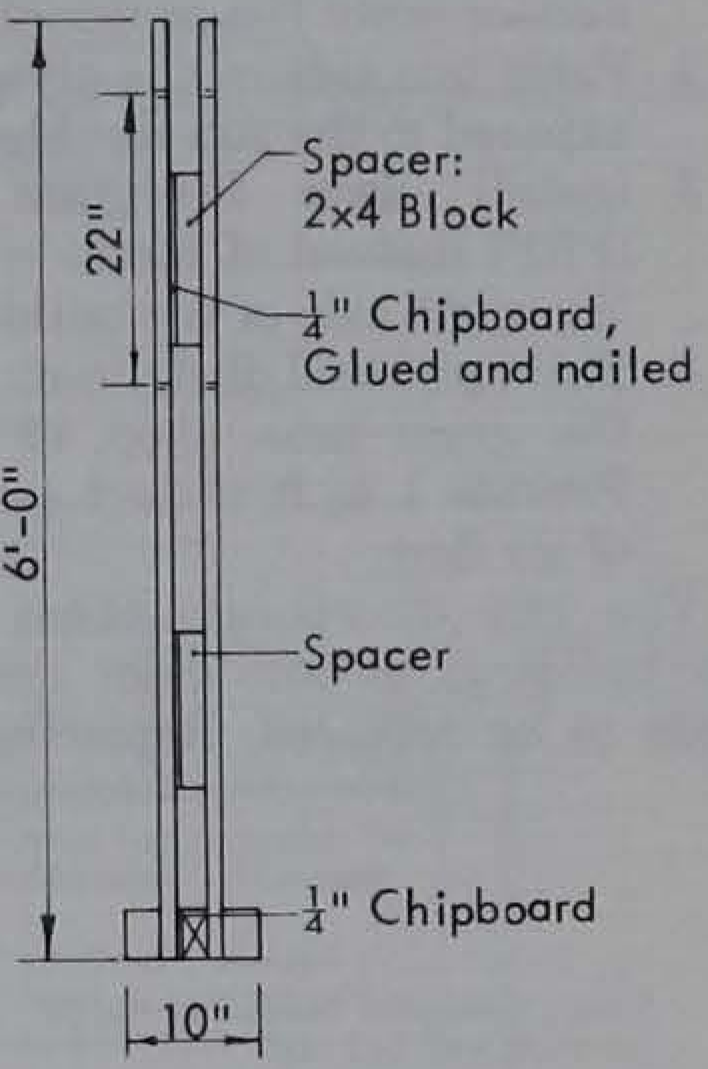
Each stand requires 3- ⅜''x6'' bolts, about ¼''x3½''x36'' chipboard, 10' of 2x4, 16' of pressure-treated 2x4, and 2- 3'' L-Brackets to fasten the collector sections.



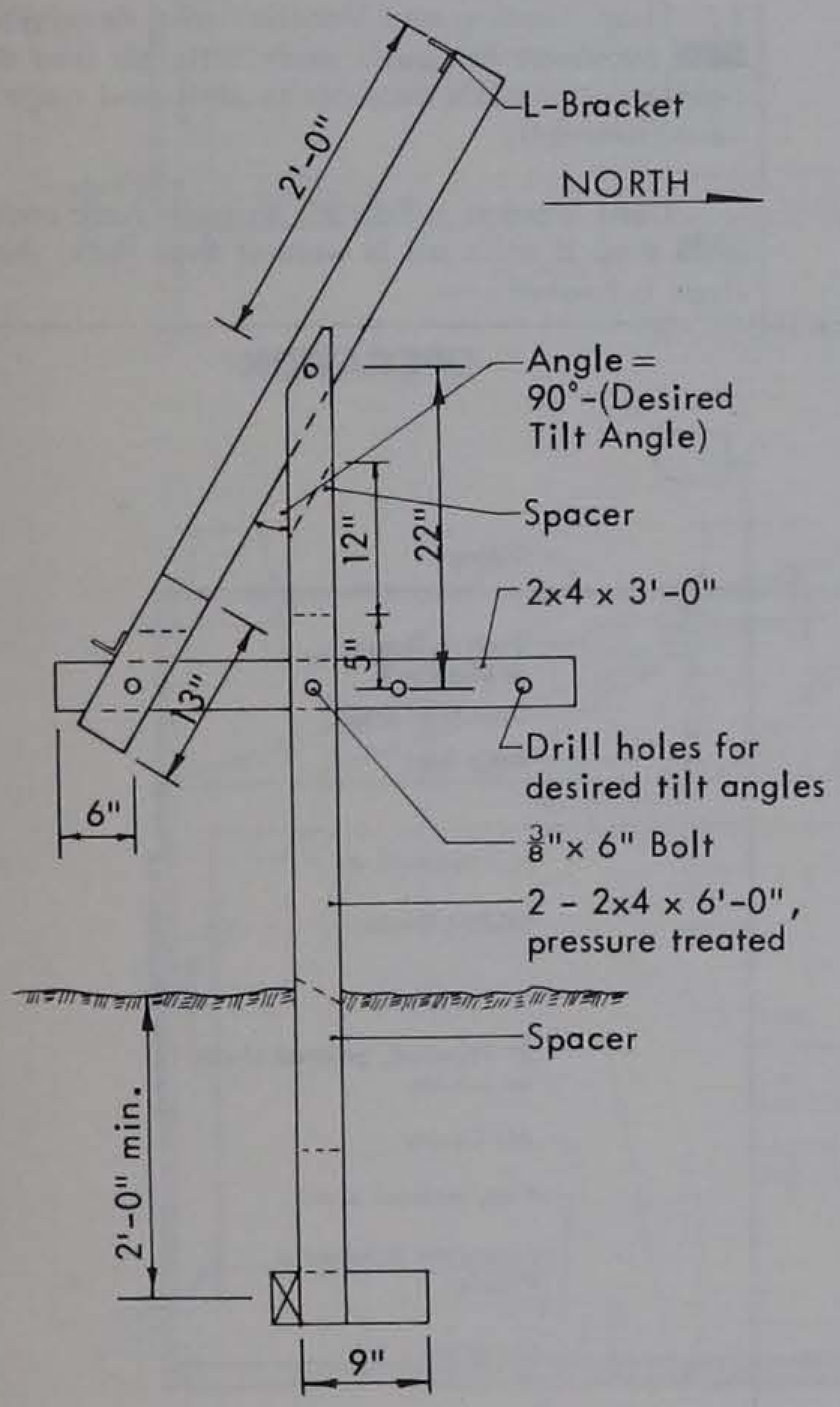
Brace



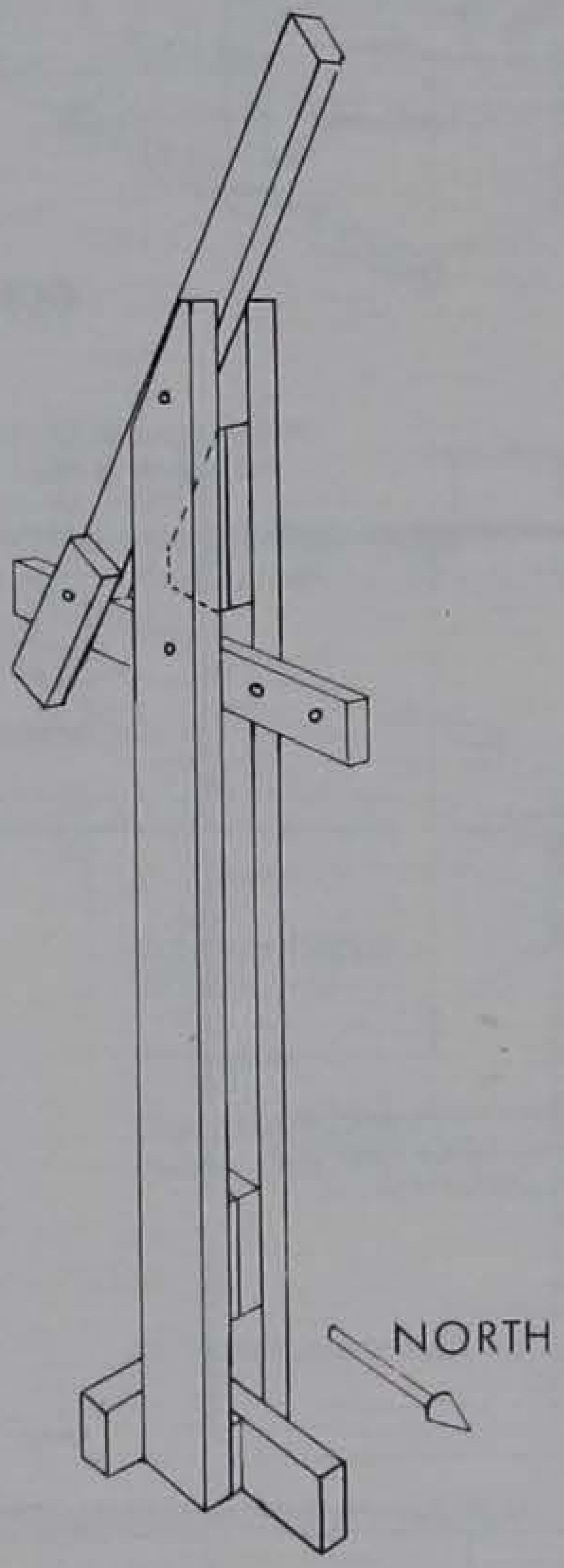
Collector Support Arm



Leg



Side View



Machine Shed with Solar Attic

The south side walls and roof slopes of east-west machine storages have large areas that can be easily modified to collect solar energy. The procedure is:

1. Install a plywood ceiling and interior sidewall on the south half of the building (install a full ceiling over the shop) and a vertical plywood divider down the center of the attic.
2. Paint one side of the plywood and all framing exposed to the sun flat black.
3. Install clear fiberglass reinforced plastic (FRP) instead of metal roofing and siding on the south side of the building.
4. Build plywood ducts to direct the heated air to the grain bins, shop, or other point of use. Provide 1 sq ft of duct area for each 1000 cfm of air flow.

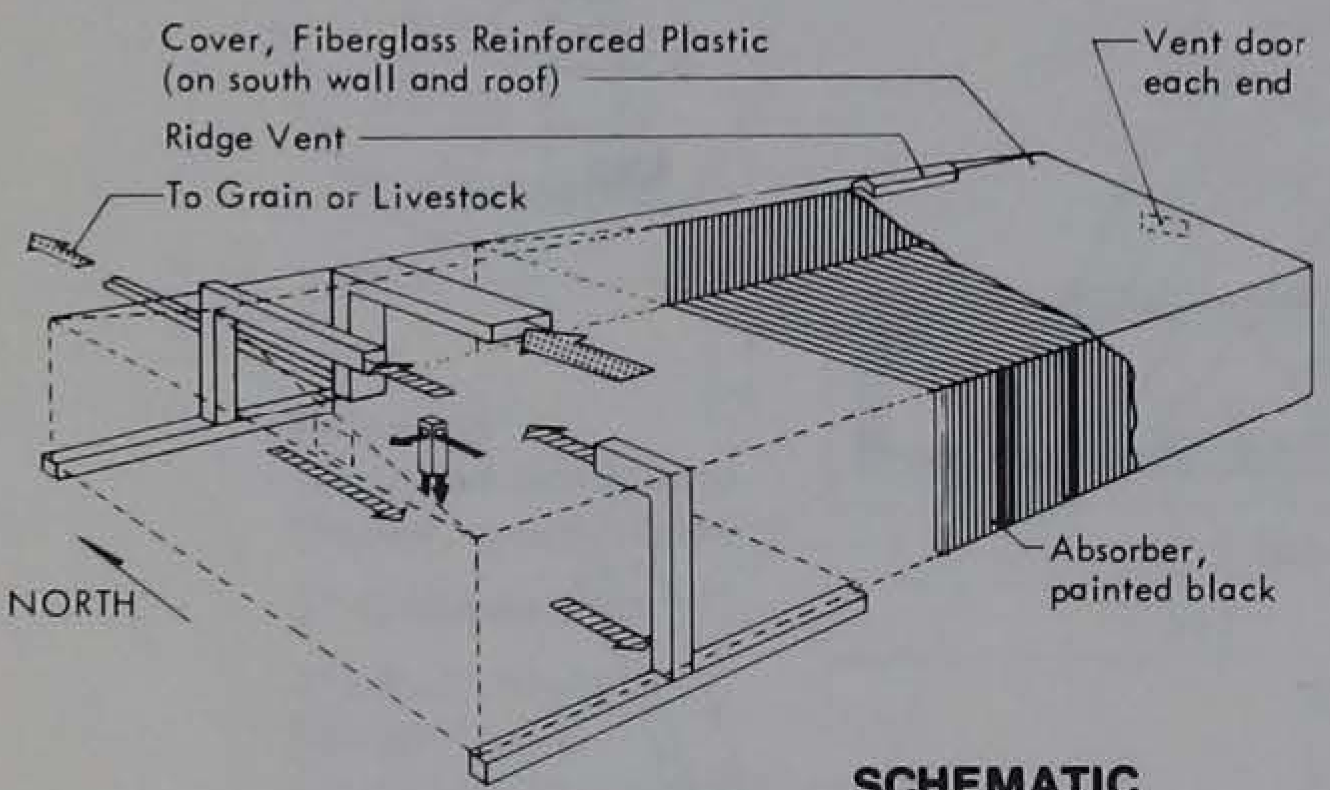
You can incorporate these solar features into new buildings or into older ones when the roofing needs to be replaced. Replacing good roofing with FRP for a solar collector is not usually economical.

The Midwest Plan Service has a plan for a 48' x 96' solar machine shed and shop (mwps-81901). It is available at a nominal charge. The illustrations here show the principles of operating a solar attic.

The plan shows the entire south roof and sidewall as a solar collector. A large building may have more collection area than required—build to meet your heating needs. (See Collector Sizing.) Average all-day efficiency for a 4/12 roof collector is about 40% and for a wall collector about 50%.

The Schematic shows how to heat both the shop air and shop floor with solar energy. It also shows ducting heated air for grain drying or heating a livestock building. The systems are independent of each other. You can install one, two, or all three of the systems.

Solar machine shed collectors have relatively low cost per square foot, but consider the following disadvantages before you decide to build one.



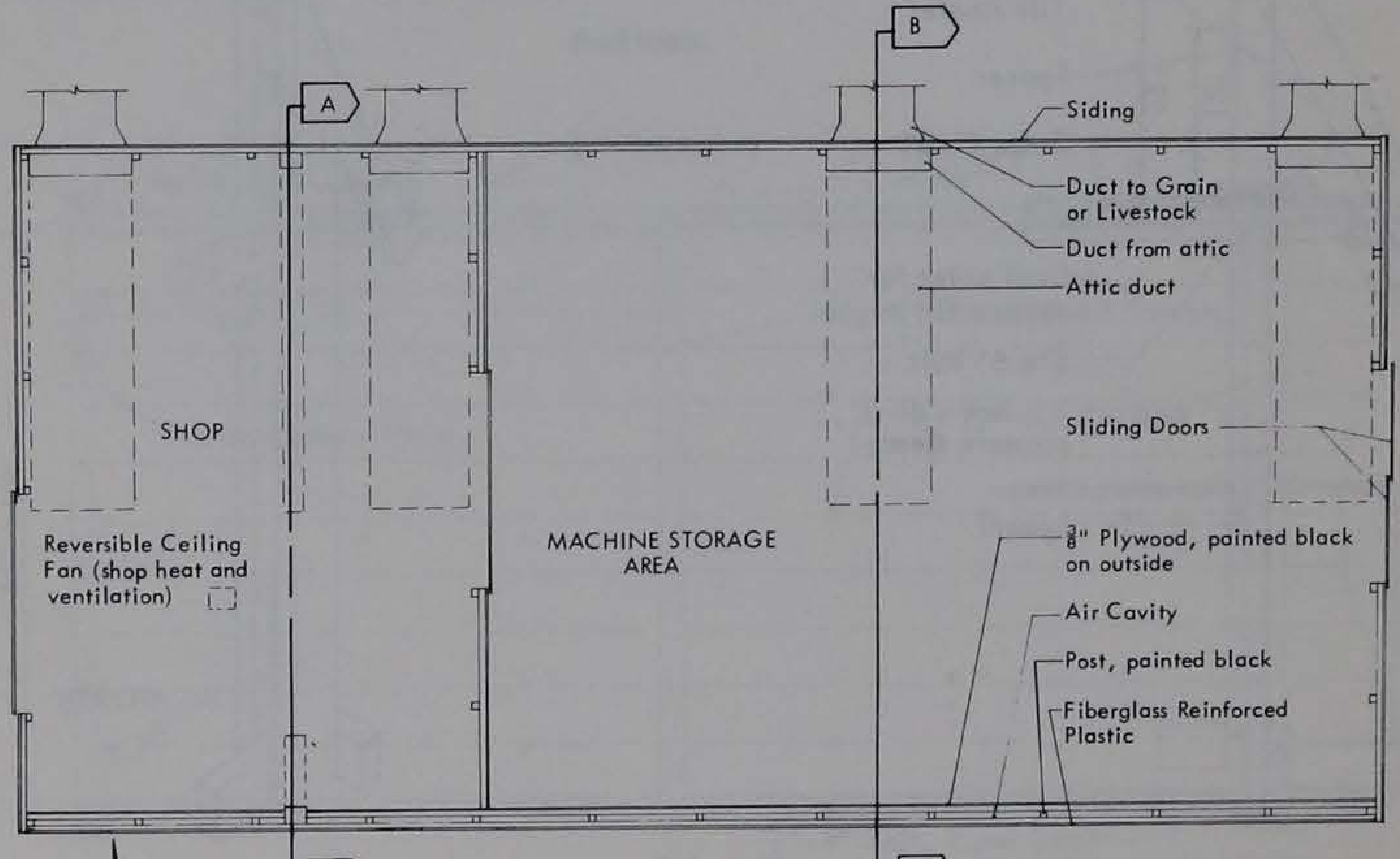
SCHEMATIC

A. Grain Drying or Livestock Building Heating- ▒ Pull attic air through north wall ducts by drying or ventilating fans.

B. Shop Heating and Ventilation - Reversible ■ overhead fan pulls warm attic air into shop (winter) - or pulls shop air to attic and ridge vent (summer).

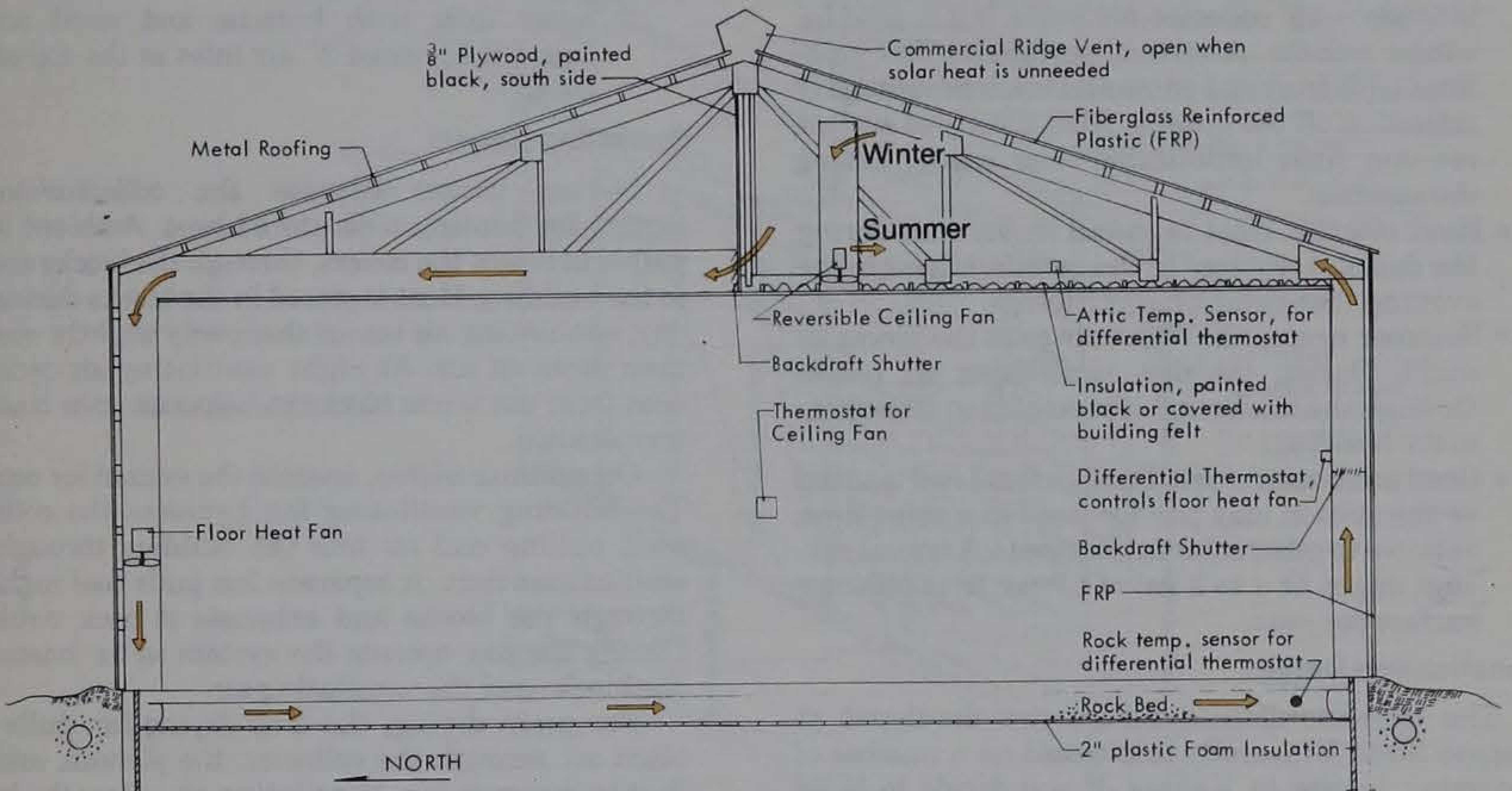
C. Heat Storage - Pull air through rock under ▥ shop if attic air is warmer than rock; shop floor is heated.

OPERATION

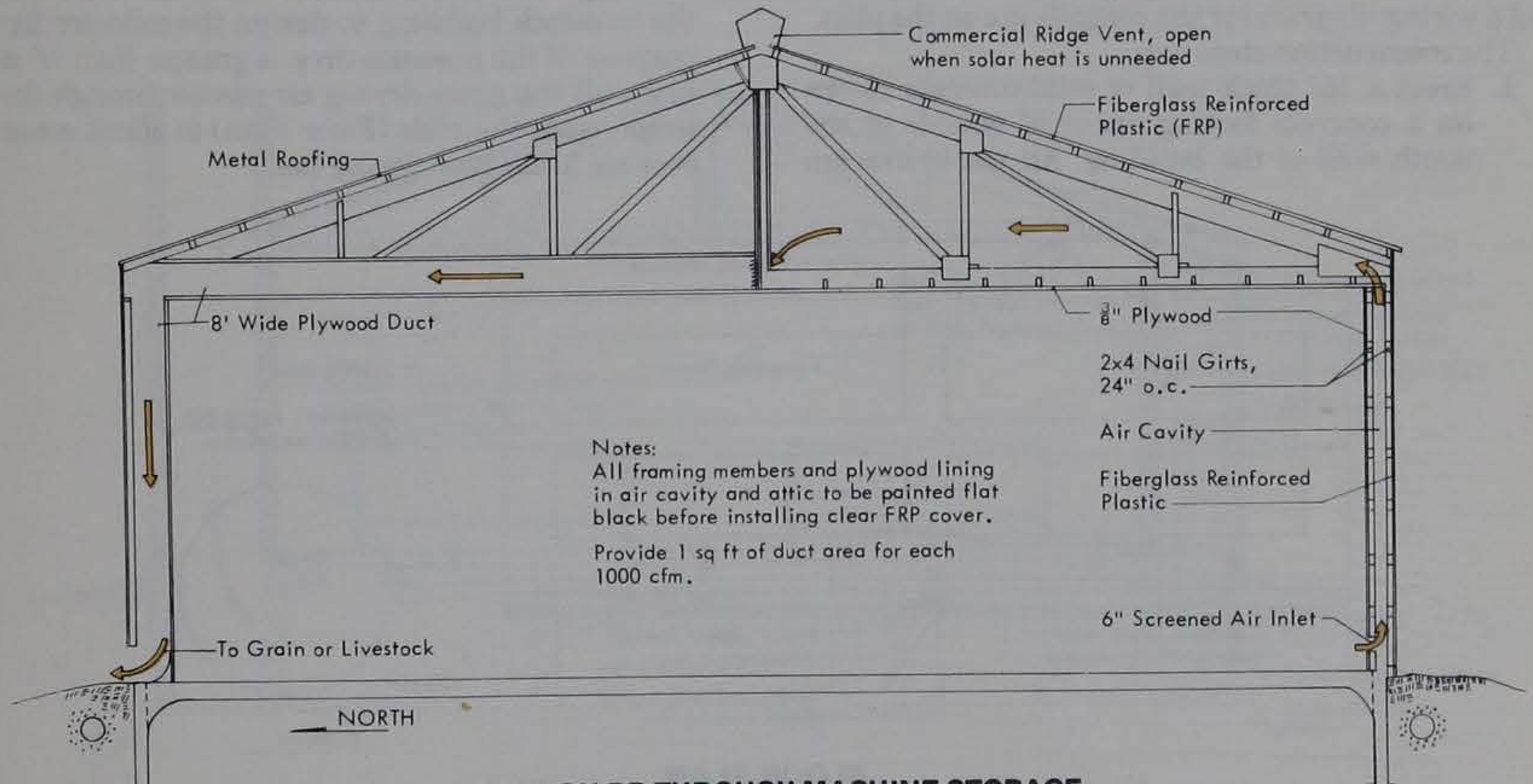


FLOOR PLAN

- Neither the typical 4/12 roof slope nor the sidewall is at the optimum angle for collecting solar energy during the grain drying and heating seasons in the North Central Region. (The optimum angle is the latitude + 15°.) So to produce the same heat, a solar collector must be larger than one at the optimum angle.
- Heat must be ducted to grain bins or livestock buildings. Keep the ducts as short as possible to minimize heat losses, pressure drops, and cost. Grain bins or a livestock building near the machine storage may not be convenient or desirable.
- Vent the solar attic in summer to allow the collected but unneeded heat to escape. Provide 1 ft^2 ridge vent per 100 ft^2 of collector and one 4' x 8' screened opening in each end of the attic. Even with the vents open, the building may be hotter than one without a solar attic.
- Frost and snow on the roof can greatly reduce solar energy collection.



SECTION AA THROUGH SHOP



Notes:
All framing members and plywood lining in air cavity and attic to be painted flat black before installing clear FRP cover.

Provide 1 sq ft of duct area for each 1000 cfm.

SECTION BB THROUGH MACHINE STORAGE

Collector with Block Wall Heat Storage

The heart of this system is a 16" thick wall of solid concrete blocks along the south side of a livestock building. The wall absorbs and stores solar heat. Advantages of this system:

- Multiuse possibilities. The collector can provide heat for grain drying in the fall and preheat the ventilating air for the livestock building in the winter.
- Small space requirement.
- A good surface for winter solar energy collection. The vertical wall is steeper than the optimum latitude +15° collector tilt angle, but is good for winter months. A vertical surface has few problems with frost and snow and takes advantage of reflection off the ground. Also, a vertical surface receives little undesirable solar energy during the summer.
- Heat storage. Heat is stored in the wall during the day and released to the ventilating air in the evening. See Solar Energy Storage.
- Summer heat sink. Night air cools the blocks at night. During the day, ventilating air passes through the blocks and is precooled on its way into the building.
- Good economic return. Enough fossil fuel is saved so the system may pay for itself in a short time, relative to other solar investments. A typical savings might be 1 to 2 gal of LP per ft^2 of collector surface per year.

Construction Details

The collector discussed here was developed at Kansas State University and tested on a number of farrowing houses in Kansas. If you decide to build this type of collector, order "20-Sow Solar Farrowing House," Plan No. 81902, from Midwest Plan Service. Construction details, more on how to use the system, and a wiring diagram for the controls are on the plan.

The construction steps are:

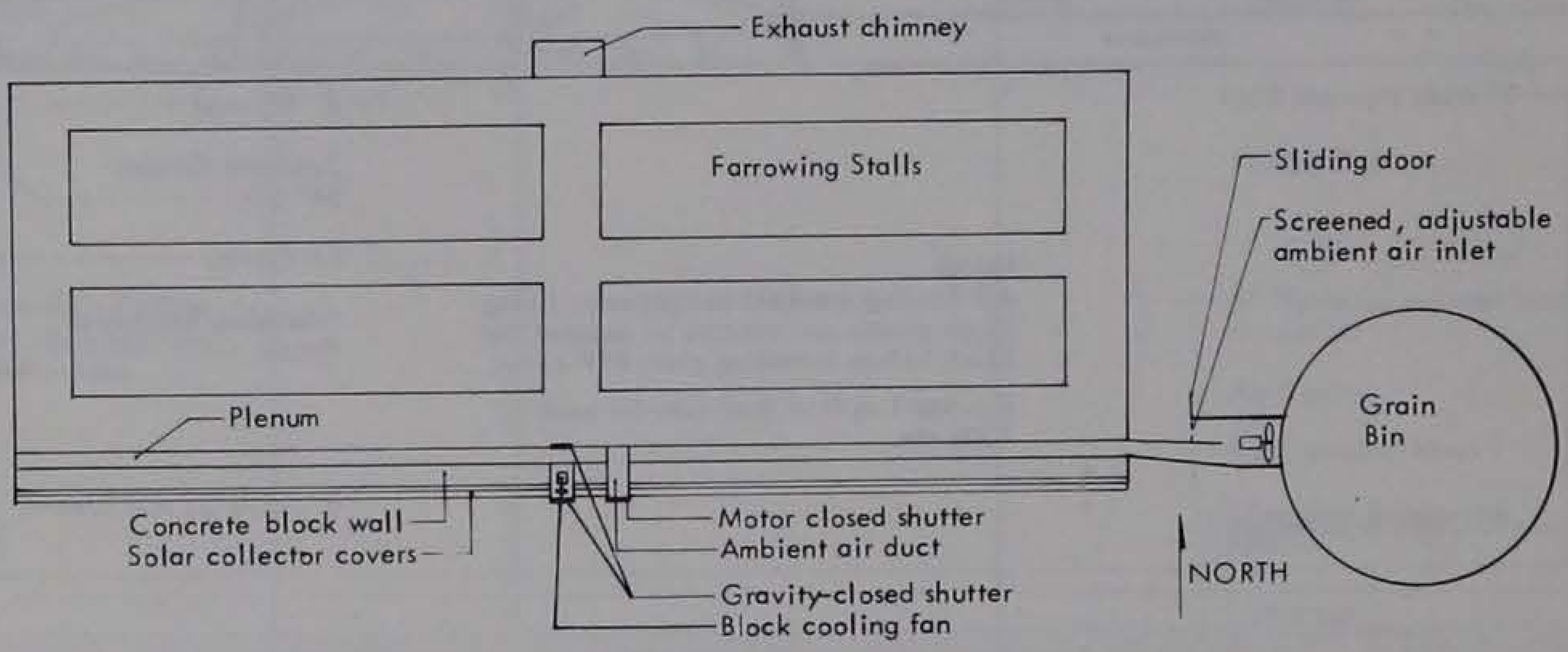
1. Erect a 16" thick wall of solid concrete blocks on a concrete footing about 6" outside of the south wall of the building. All the blocks are perpendicular to the wall. Mortar only the horizontal joints and leave 3/16" vertical gaps between the blocks.
2. Spray the south surface of the wall with two coats of flat black paint.
3. Attach vertical 2x2s to the south side of the wall.
4. Fasten a layer of transparent cover material to the 2x2s. Leave a 4" air gap at the bottom.
5. Attach another framework of 2x2s over the first—sandwiching the cover material between them.
6. Fasten another layer of cover material to the outer 2x2s with battens and wood screws. Leave a screened 2" air inlet at the top of this cover.

Operating Details

During winter operate the collector/storage system for heating with stored heat. Ambient air is pulled between the covers, through the blocks and into the building. Heat is stored in the blocks during the day; ventilating air leaves them only slightly warmer than ambient air. At night ventilating air picks up heat from the warm blocks to help maintain building temperature.

On summer nights, operate the system for cooling. The building ventilating fan bypasses the collector wall, pulling cool air into the building through the ambient air duct. A separate fan pulls cool night air through the blocks and exhausts it back outdoors. During the day operate the system as for heating—the blocks cool the ventilating air.

For grain drying, the crop drying fan pulls ambient air through the collector, the plenum, and the duct to the grain bin. Ventilating air enters the building through the ambient air duct. Grain drying usually requires much higher airflow than a livestock building. The main use for this collector is heating the livestock building, so design the collector for that purpose. If the pressure drop is greater than 1/2" water when all the grain drying air passes through the collector, open the slide (Floor Plan) to admit some outdoor air to the crop drying fan.



FLOOR PLAN

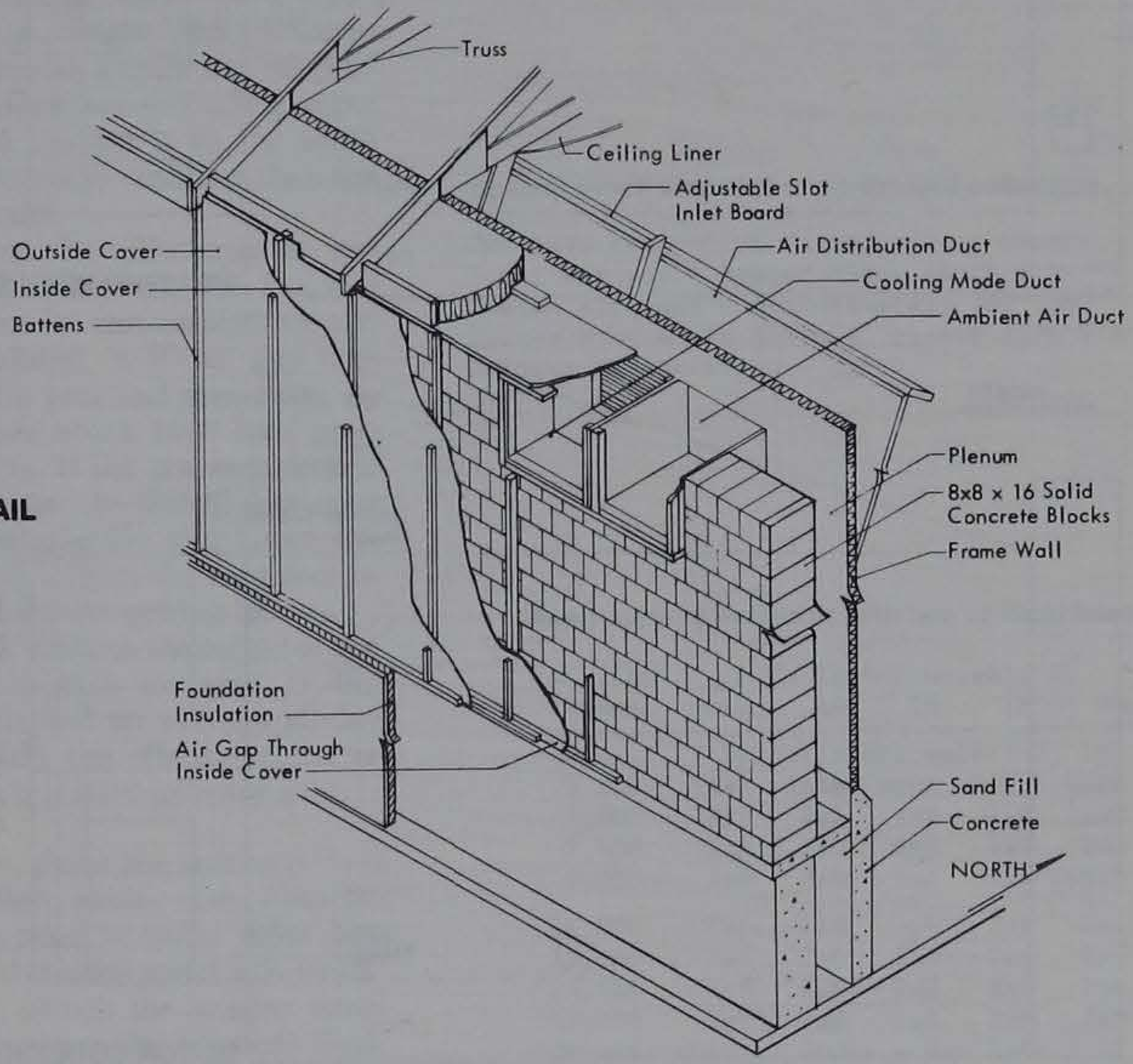
System Performance

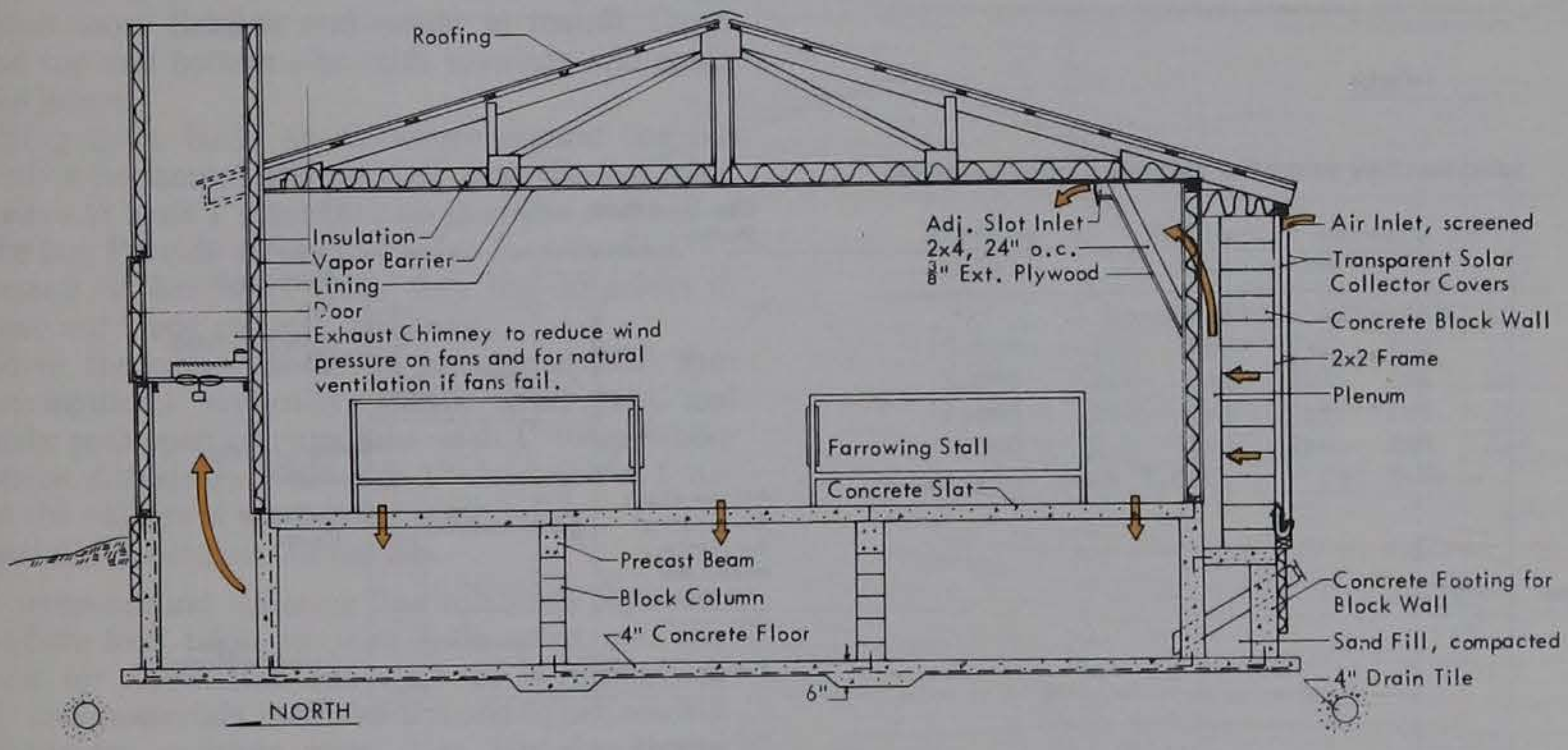
As tested at Kansas State, the block wall provided 32 Btu of heat storage per degree Fahrenheit temperature change per sq ft of collector surface area. At 1 cfm per sq ft of collector area, peak solar insolation was about 9 hours ahead of the peak temperature of the ventilating air and even further ahead of the peak temperature rise. Under Kansas conditions, average all-day collector efficiency was:

Airflow	Efficiency
1 cfm/ft^2	45%
2 cfm/ft^2	55%
3 cfm/ft^2	60%
4 cfm/ft^2	62%
5 cfm/ft^2	63%

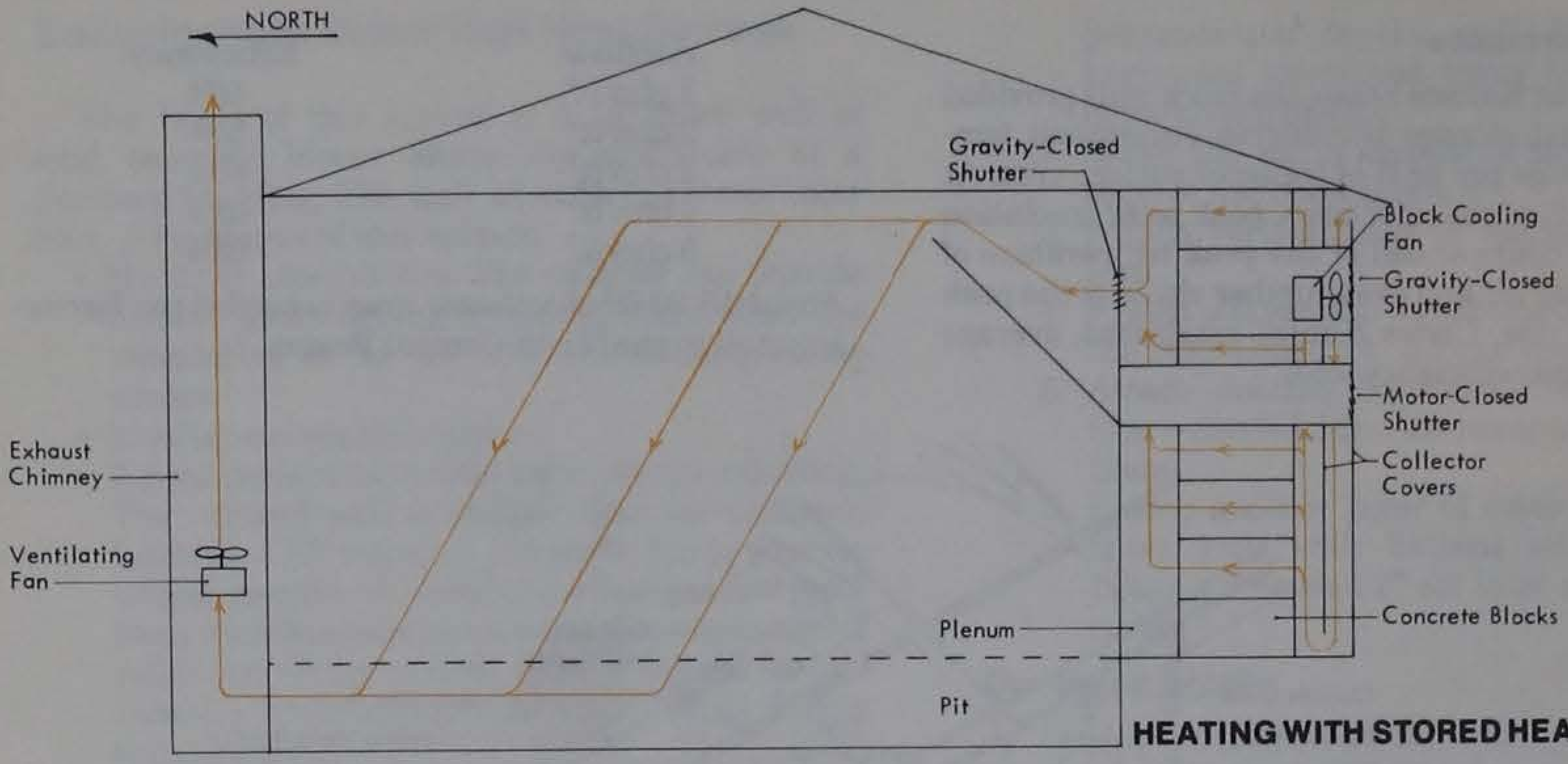
About 15-20 ft^2 of collector area is needed per farrowing stall in the North Central Region.

SOLAR WALL DETAIL

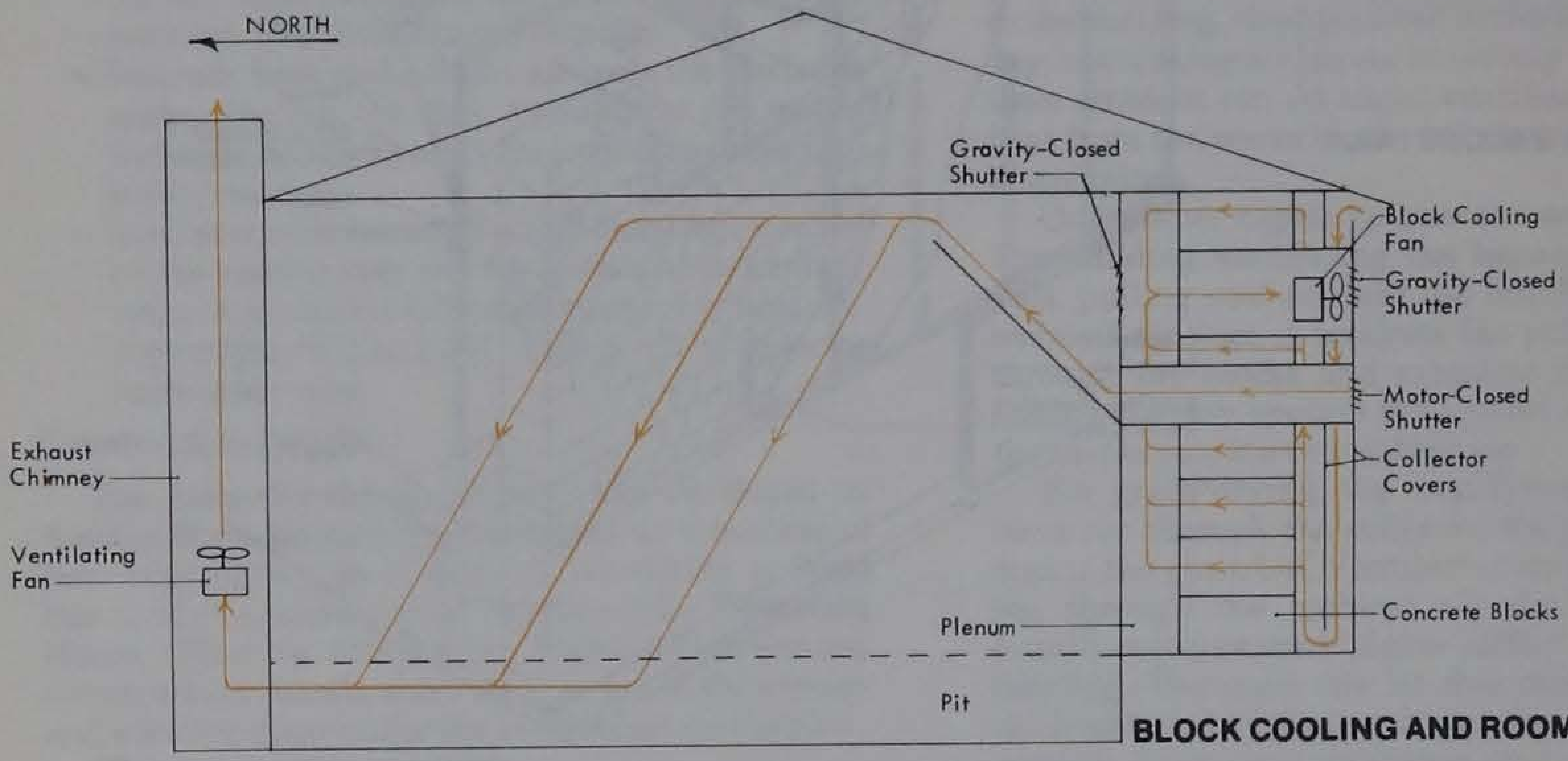




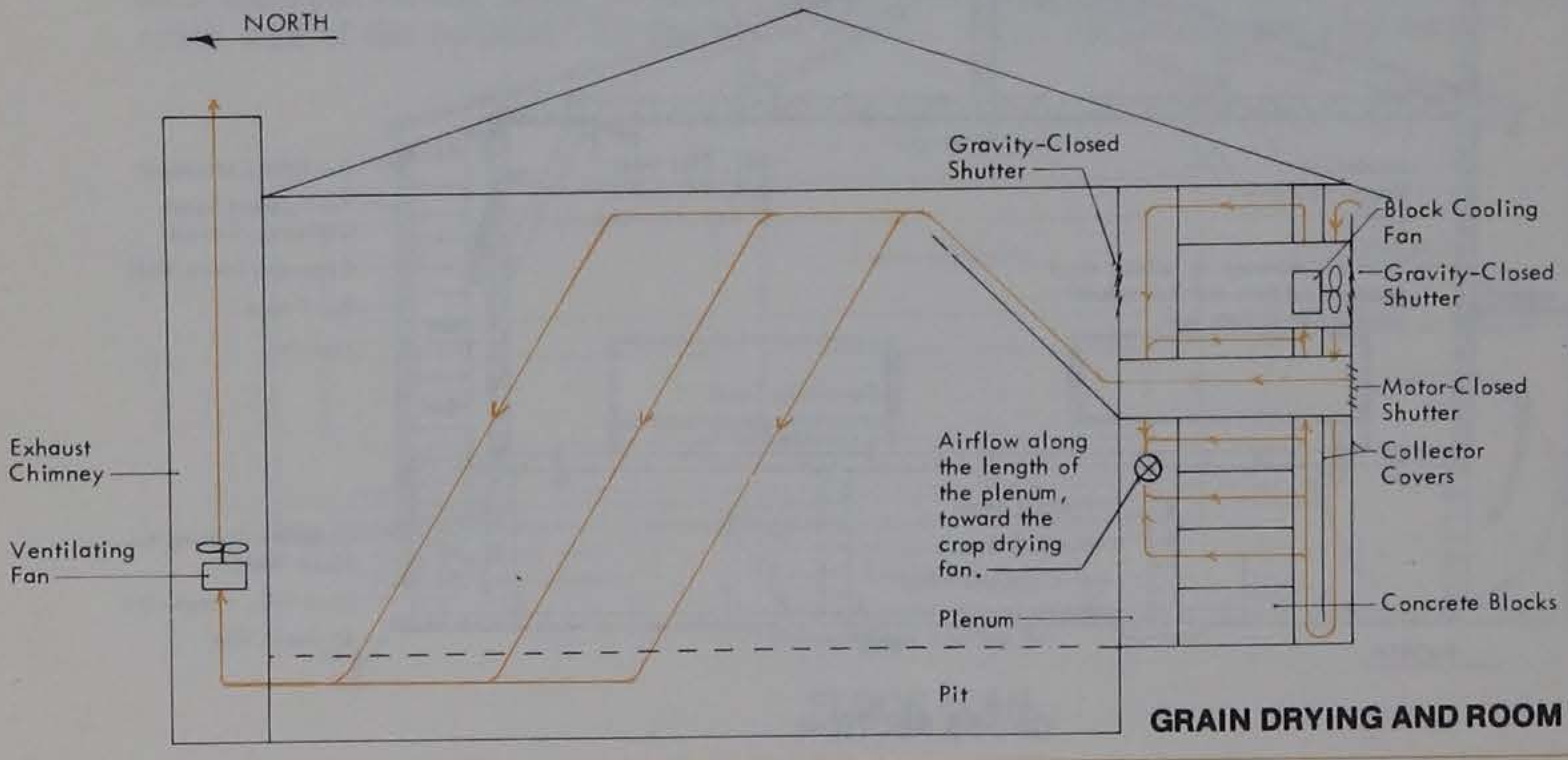
CROSS SECTION



HEATING WITH STORED HEAT, OR COOLING



BLOCK COOLING AND ROOM VENTILATION



GRAIN DRYING AND ROOM VENTILATION

Wrap-Around Solar Collector

You can build a solar collector for grain drying on the bin wall and minimize the length of air ducts. Wrap a covered-plate collector around the southern two-thirds of the bin; completely cover the drying fan. The fan draws grain-drying air through the collector, between the transparent cover and blackened bin wall.

No more than half of the collector faces the sun at any time. Installed Collector Area = ⅔ x 3.14 x Bin Diameter x Collector Height. But, Effective Collector Area = Bin Diameter x Collector Height.

It is best if the door, ladder, and unloading auger are on the north side and the fan is on the south side. The fan can be to the east or west, but then the collector has only one air inlet.

Size the air gap between the collector cover and bin wall so the air velocity is between 500 fpm and 1000 fpm. Spacer block sizes for various airflows and collector heights are tabulated. A 9" air gap (2x8 spacer plus two 1x2s) is the practical maximum. As air velocity increases above about 1000 fpm, pressure drop becomes excessive. If the pressure drop is greater than ½" of water, open the sliding door near the fan inlet to admit outside air and lower the pressure drop to less than ½". Open the vent door in summer to keep the collector from getting too hot.

For energy calculations, assume the collector is a vertical, south-facing wall with an area of bin diameter x collector height and an average all-day efficiency of 70%. Note that the effective collector area is only about half the installed collector area.

Construction steps:

1. If the bin is fairly new, paint the southern ⅔ of the outer bin wall flat black. See Absorber Materials. You don't need to paint older bins with well weathered galvanized metal side walls.
2. After the paint is dry, attach the wooden cover supports (steel Z sections can also be used). Soak the knot-free 1x2s in water for a day to make them more flexible and easier to install. Cover the top and bottom ribs with paneling and caulk the joints.
3. Using 2x2s, build an enclosure around the fan with a horizontal sliding door near the fan inlet. Leave at least 1' clearance on the sides and end of the fan. Provide access to the fan for servicing.
4. Install ¼" hardware cloth over the air inlets to keep out birds, rodents, and trash.
5. Cover the ribs with flat or corrugated FRP. Run corrugations vertically. Caulk sheet laps and ends; seal open corrugations with 1" foam rubber strips. Attach the FRP with 1" wood screws 1' o.c., in the valleys of corrugated material.
   Install flashing on the top rib.

A wrap-around collector has relatively low cost per square foot, takes up very little space, and has no long air ducts. But, the collector is difficult to build, uses materials inefficiently, and is not readily adaptable for multiple uses. Also, bin size limits available collection area. As the diameter of a bin increases, its volume increases faster than its surface area. For example, a 36' bin holds four times as much grain as an 18' bin, but has only twice the surface area. Collectors on large bins provide less energy per bushel than collectors on small bins. If you have a long east-west building near the grain bin, a collector on the south wall is probably a better investment than a wrap-around collector.

Spacer block sizes for wrap-around collectors.

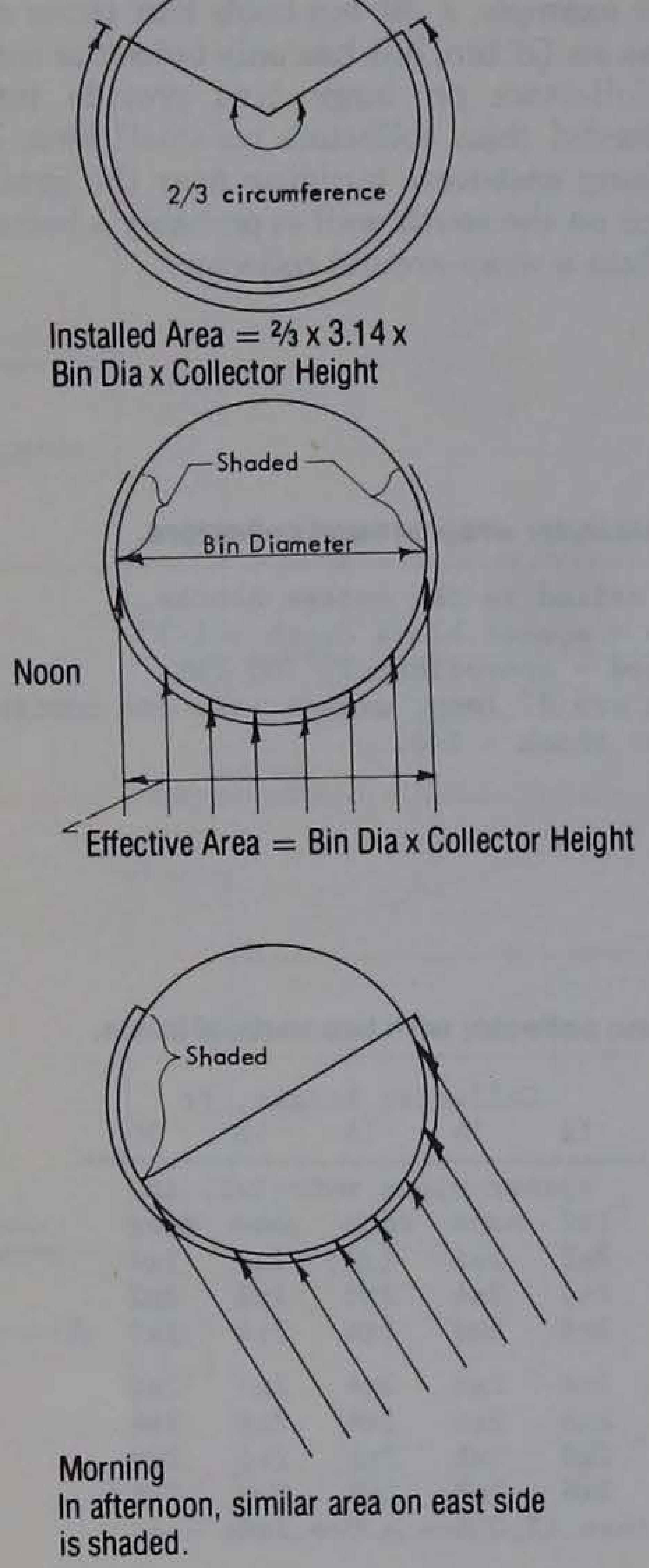
Two 1x2s are nailed to the spacer blocks.
Total air gap = spacer block depth + 1.5".
Design airspeed = approximately 700 fpm.
Spacer blocks are 8" long, except 1x2s are continuous.
Maximum spacer block - 2x8.

Wrap-around collector with two vertical inlets.

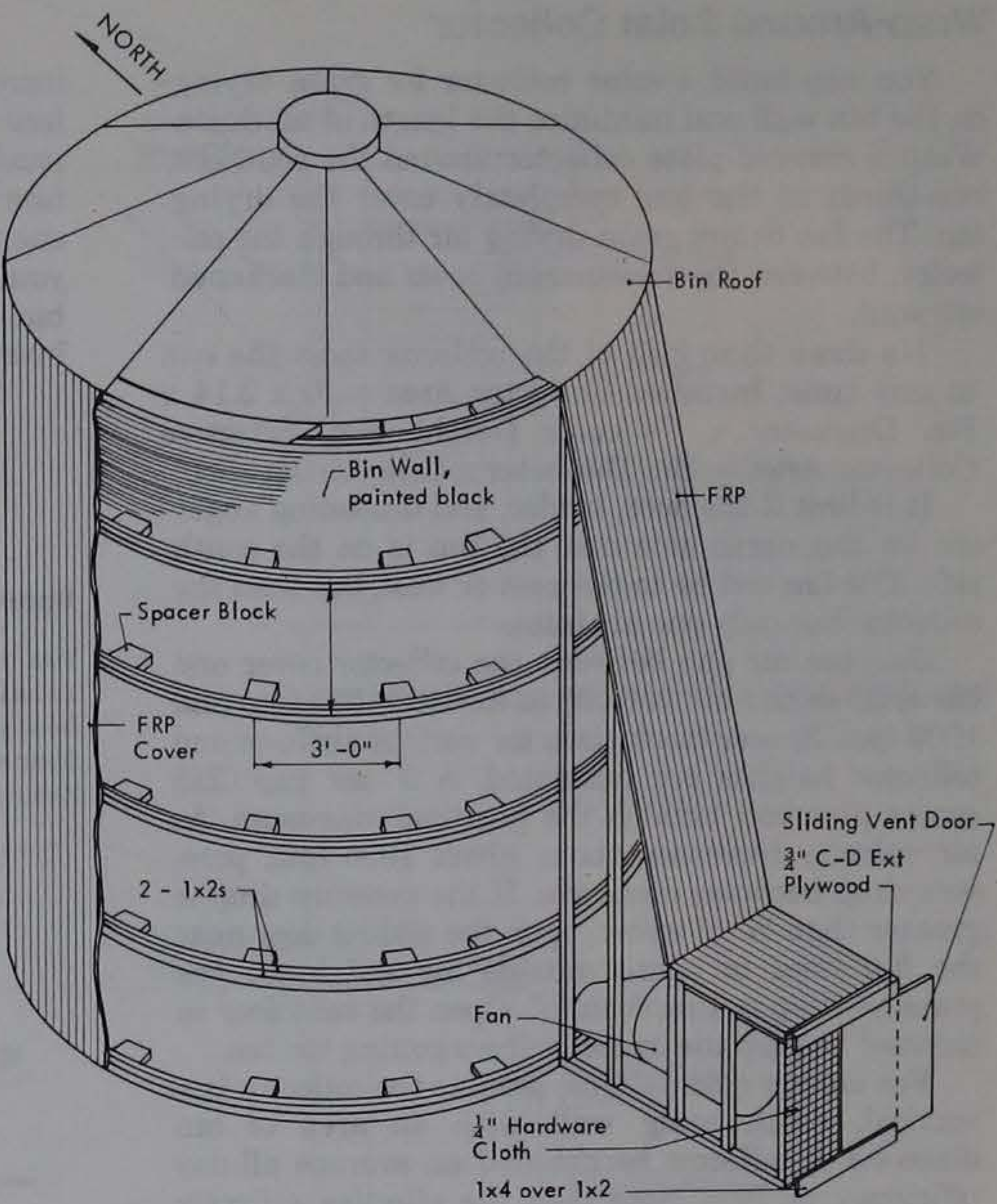
Airflow (cfm)	Collector height, ft 12	14	16	18	20
	Spacer block material, in				
3,000	1x2	none	none	none	none
5,000	2x2	2x2	1x2	1x2	1x2
7,000	2x4	2x4	2x2	2x2	2x2
9,000	2x6	2x4	2x4	2x4	2x2
11,000	2x6	2x6	2x4	2x4	2x4
13,000	2x8	2x6	2x6	2x6	2x4
15,000	2x8	2x8	2x8	2x6	2x6
17,000	2x8	2x8	2x8	2x8	2x6
Greater than 17,000:- - Use 2x8s - -					

Wrap-around collector with one vertical inlet.

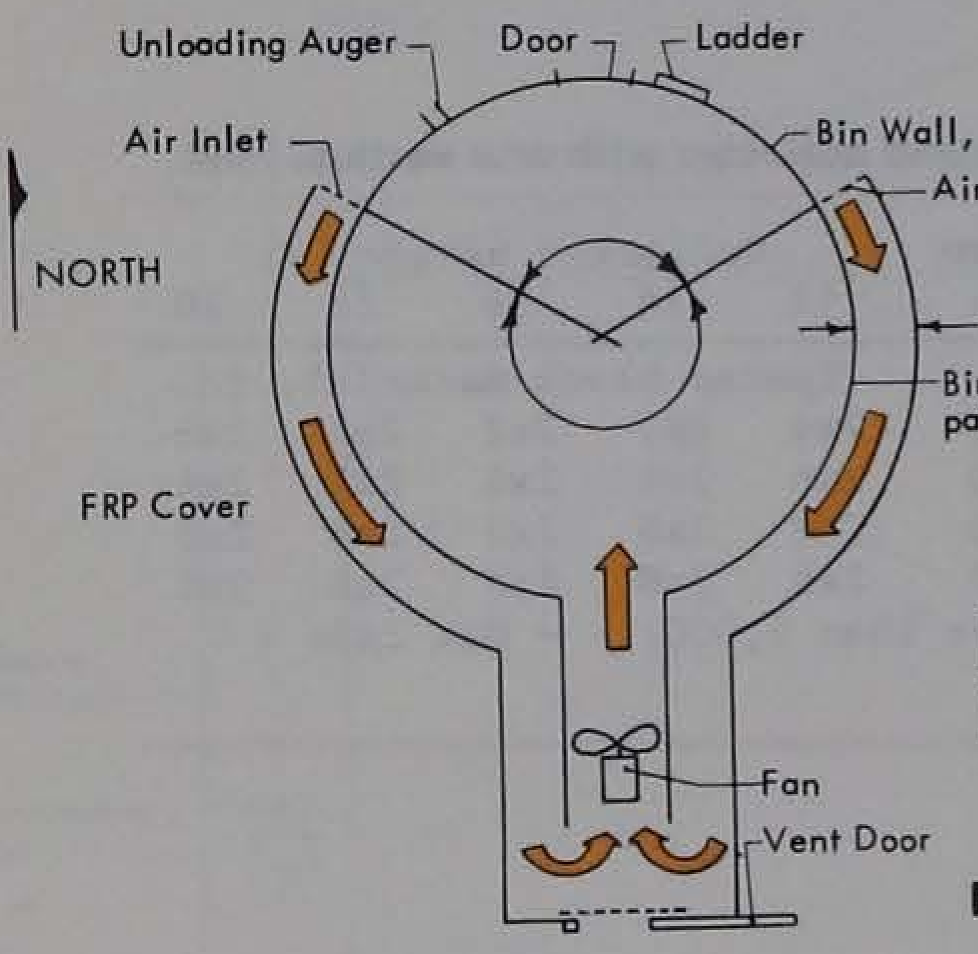
Airflow (cfm)	Collector height, ft 12	14	16	18	20
	Spacer block material, in				
3,000	2x4	2x2	2x2	2x2	1x2
5,000	2x6	2x6	2x4	2x4	2x4
7,000	2x8	2x8	2x6	2x6	2x6
9,000	2x8	2x8	2x8	2x8	2x6
Greater than 9,000: - - Use 2x8s - -					



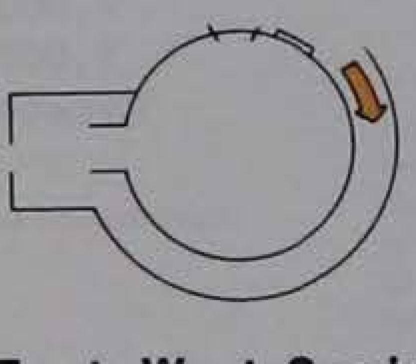
Tracking effect of a wrap-around collector.



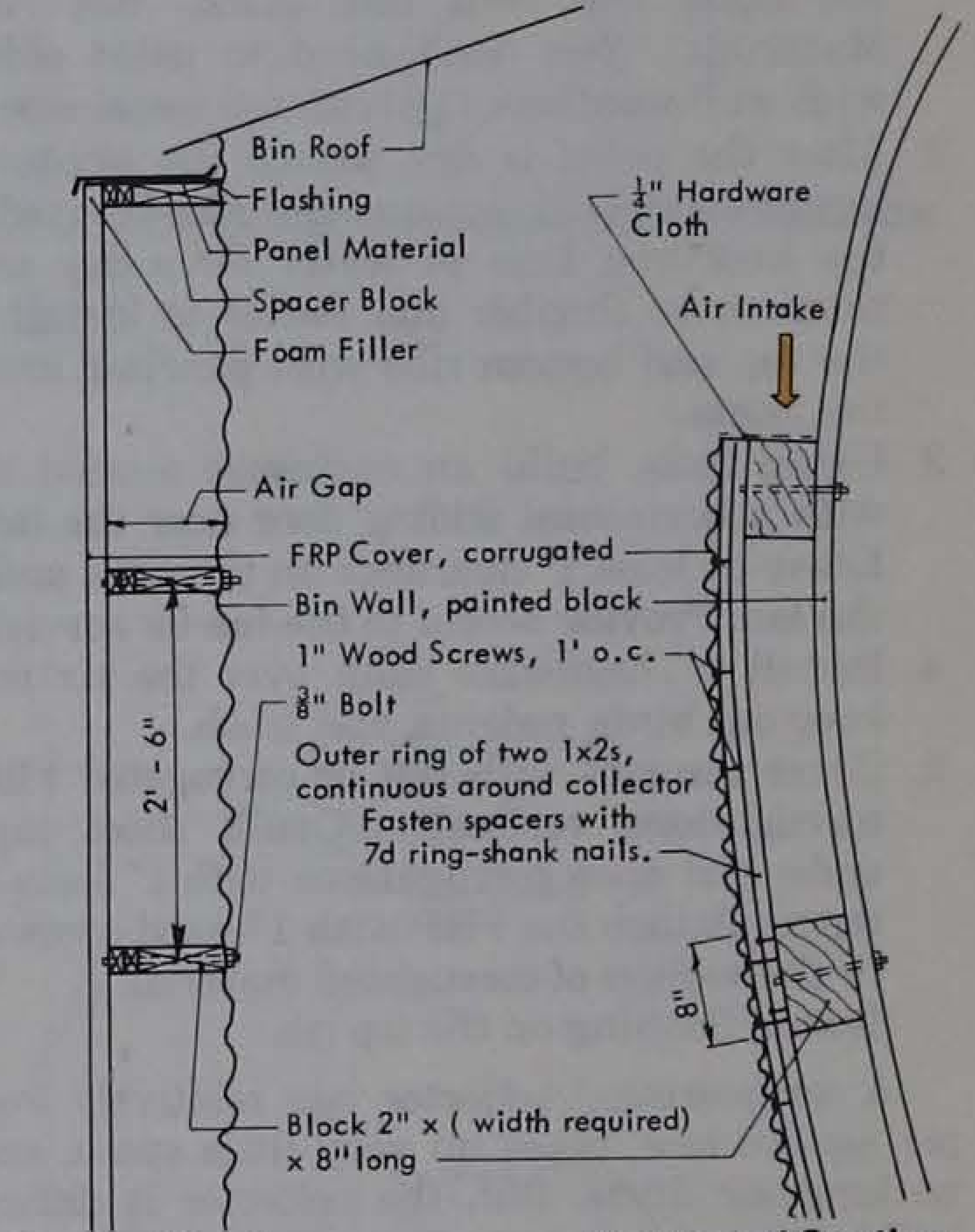
Schematic of wrap-around collector. Fan to South.



Fan to South. Two vertical air inlets.



Fan to West. One inlet.



Vertical Section **Horizontal Section**

Cross section of a wrap-around collector.

APPENDIX

Table 22. Hourly, clear day solar radiation.

Data are for average clear days—on exceptionally clear days values 15% greater are possible. Values include direct + diffuse radiation, Btu/hr-ft², on south-facing surfaces. Developed by MWPS with technique from 1978 ASHRAE Applications Handbook. Measure collector tilt angles from horizontal. Surfaces with a latitude + 15° tilt angle receive the most energy during the grain drying and space heating seasons. Use this table to calculate sunny day collector output at your latitude. Table times are solar time.

Example: Find the maximum temperature rise from a 2400-ft² solar collector on a south-facing 4/12 roof slope on Oct. 15 near Bismarck, ND. Airflow is 10,000 cfm.

Answer: The maximum temperature rise is at noon on sunny days. Bismarck's latitude is a little less than 47°—use Table 22f for 46°. The closest tabulated date is Oct. 21.

Noon hour, clear day solar radiation on 4/12 slope = 242 Btu/hr-ft².

The collector plan gives an average all day efficiency of 40%. Assume the noon hour efficiency is 5 percentage points greater.

Noon hour efficiency = 40% + 5% = 45%.

Maximum temperature rise

$$= \frac{\text{Collector area} \times \text{Noon hour, clear day solar radiation} \times \text{Noon hour collector efficiency}}{1.1 \times \text{Collector airflow}}$$

$$= \frac{2400\ \text{ft}^2 \times 242\ \text{Btu/hr-ft}^2 \times 0.45}{1.1 \times 10{,}000\ \text{cfm}} = \textbf{about 24F}$$

(Note: This same collector produces a 24-hr. average temperature rise of only 4F over the grain drying season. See example in Table 23.)

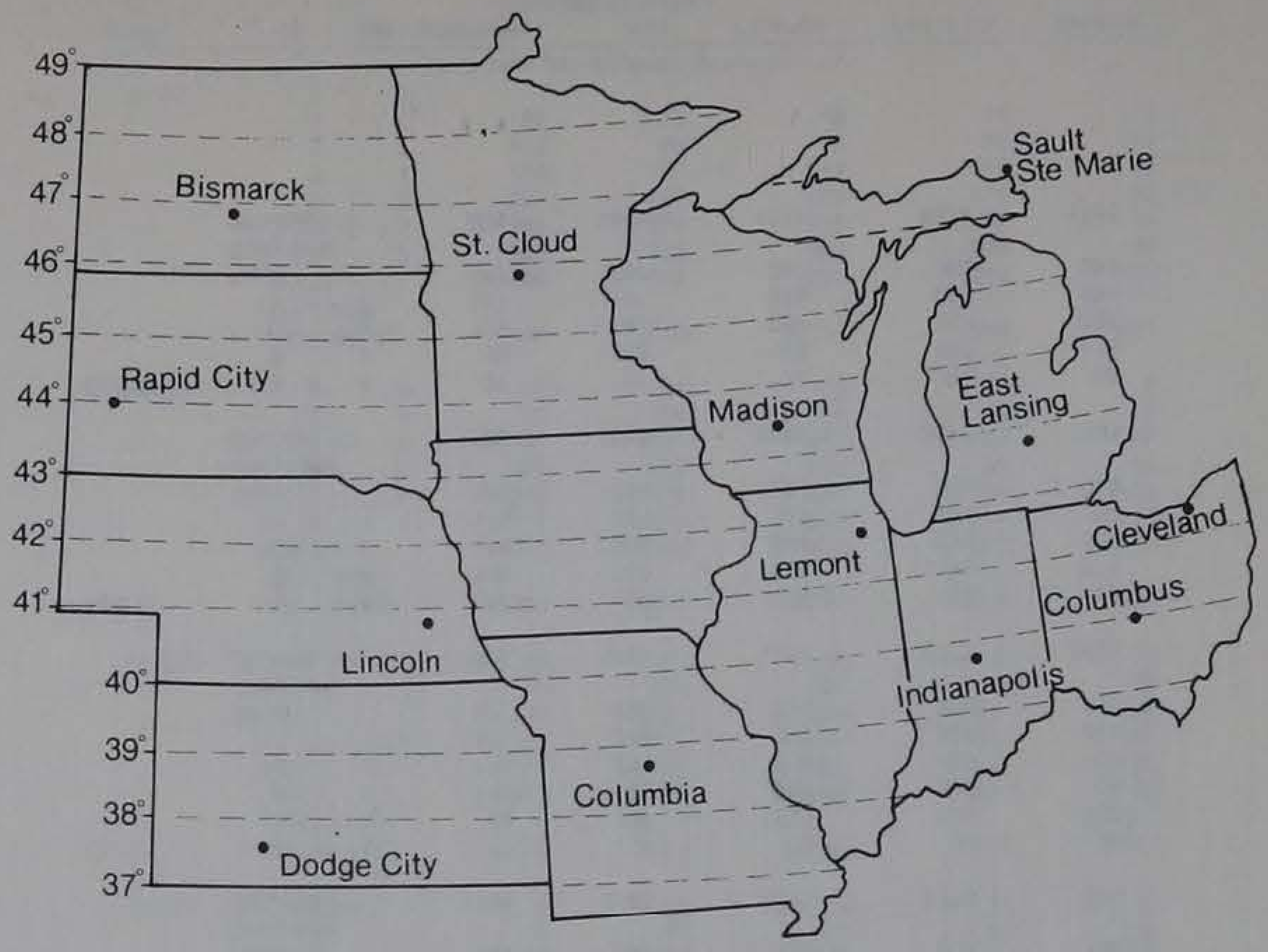


Fig 41. Latitude lines in the North Central region.
Solar radiation data were available for the cities shown and are tabulated in Table 23.

Table 22a. 36° North Latitude

			Collector tilt angle				
Date	**AM**	**PM**	**Horizontal**	**4/12**	**Latitude**	**Lat. +15**	**Vertical**
			------Hourly clear day radiation, Btu/hr-ft²------				
Jan 21	8	4	42	71	92	104	103
	9	3	101	150	184	199	178
	10	2	148	209	248	264	224
	11	1	177	245	287	303	251
	Noon		187	257	301	316	259
	Daily total (Btu/day-ft²)		1124	1608	1923	2056	1770
Feb 21	7	5	14	21	27	30	29
	8	4	82	110	127	133	109
	9	3	144	186	210	215	165
	10	2	192	245	272	276	204
	11	1	223	281	311	314	228
	Noon		233	293	324	327	236
	Daily total (Btu/day-ft²)		1542	1981	2218	2262	1705
Mar 21	7	5	50	56	57	55	33
	8	4	121	139	144	138	84
	9	3	184	213	221	212	129
	10	2	232	269	280	269	164
	11	1	263	305	317	305	186
	Noon		273	317	330	317	193
	Daily total (Btu/day-ft²)		1972	2281	2368	2275	1385
April 21	6	6	18	13	7	6	4
	7	5	87	82	70	56	10
	8	4	156	158	146	126	43
	9	3	215	225	215	192	80
	10	2	260	278	269	243	109
	11	1	289	311	303	276	128
	Noon		298	322	315	287	135
	Daily total (Btu/day-ft²)		2348	2456	2339	2085	883
May 21	5	7					
	6	6	43	30	15	13	8
	7	5	112	97	75	52	13
	8	4	176	167	144	115	15
	9	3	231	229	207	174	45
	10	2	274	278	257	221	72
	11	1	300	308	288	251	89
	Noon		309	319	299	261	94
	Daily total (Btu/day-ft²)		2581	2538	2273	1914	578
June 21	5	7					
	6	6	53	36	17	16	10
	7	5	119	101	76	50	14
	8	4	182	169	142	110	16
	9	3	235	229	203	166	33
	10	2	276	275	250	211	58
	11	1	302	305	280	240	74
	Noon		310	315	290	250	79
	Daily total (Btu/day-ft²)		2643	2545	2228	1837	490
Jul 21	5	7					
	6	6	43	30	15	14	8
	7	5	110	96	75	52	14
	8	4	174	165	143	114	16
	9	3	228	226	204	172	45
	10	2	270	274	253	217	71
	11	1	296	304	284	247	87
	Noon		305	314	294	257	93
	Daily total (Btu/day-ft²)		2548	2503	2241	1888	577
Aug 21	6	6	17	12	7	7	4
	7	5	85	80	69	55	12
	8	4	152	154	143	123	42
	9	3	210	220	209	186	78
	10	2	255	271	262	236	106
	11	1	282	303	295	268	125
	Noon		292	314	307	279	131
	Daily total (Btu/day-ft²)		2295	2394	2277	2029	866
Sept 21	7	5	47	52	53	51	31
	8	4	117	133	137	131	80
	9	3	178	204	212	203	124
	10	2	225	259	269	258	157
	11	1	254	294	305	293	179
	Noon		264	306	318	305	186
	Daily total (Btu/day-ft²)		1905	2193	2270	2178	1326
Oct 21	7	5	12	18	23	25	24
	8	4	78	105	121	126	103
	9	3	140	180	202	207	158
	10	2	187	237	263	266	197
	11	1	217	273	301	304	221
	Noon		227	285	314	316	229
	Daily total (Btu/day-ft²)		1495	1910	2132	2172	1633
Nov 21	5	4	41	69	89	100	98
	9	3	100	147	180	194	174
	10	2	146	205	244	259	220
	11	1	175	241	283	298	246
	Noon		185	254	296	311	255
	Daily total (Btu/day-ft²)		1108	1580	1885	2013	1731
Dec 21	8	4	27	51	71	82	86
	9	3	83	133	168	186	175
	10	2	129	191	234	253	226
	11	1	157	227	273	293	254
	Noon		167	240	287	306	263
	Daily total (Btu/day-ft²)		959	1445	1777	1934	1745

Table 22b. 38° North Latitude

			Collector tilt angle				
Date	AM	PM	Horizontal	4/12	Latitude	Lat. + 15°	Vertical
			------Hourly clear day radiation, Btu/hr-ft^2------				
Jan 21	8	4	35	62	84	95	94
	9	3	92	141	178	193	175
	10	2	138	199	243	259	224
	11	1	166	235	283	298	252
	Noon		176	247	296	311	262
	Daily total (Btu/day-ft^2)		1038	1522	1871	1999	1753
Feb 21	7	5	11	17	22	25	24
	8	4	76	104	124	130	108
	9	3	137	180	207	212	166
	10	2	184	238	269	273	208
	11	1	213	274	308	311	233
	Noon		223	286	321	324	242
	Daily total (Btu/day-ft^2)		1463	1911	2180	2223	1721
Mar 21	7	5	48	54	56	53	34
	8	4	117	136	142	136	87
	9	3	178	209	219	210	134
	10	2	225	265	278	267	170
	11	1	255	300	315	303	193
	Noon		265	312	328	315	201
	Daily total (Btu/day-ft^2)		1913	2241	2349	2256	1435
April 21	6	6	19	14	7	7	4
	7	5	88	83	70	56	10
	8	4	154	158	146	126	47
	9	3	212	224	214	191	86
	10	2	256	276	268	242	117
	11	1	284	309	302	274	137
	Noon		293	320	314	286	144
	Daily total (Btu/day-ft^2)		2318	2449	2330	2075	946
May 21	5	7					
	6	6	46	32	15	13	8
	7	5	113	100	75	52	13
	8	4	176	169	144	115	19
	9	3	230	230	207	174	52
	10	2	271	278	256	220	80
	11	1	297	308	287	250	98
	Noon		306	318	298	260	104
	Daily total (Btu/day-ft^2)		2573	2553	2267	1908	644
June 21	5	7	2	1	1	1	1
	6	6	56	39	18	16	10
	7	5	121	104	76	50	14
	8	4	182	171	142	110	16
	9	3	234	230	202	166	40
	10	2	274	276	249	210	66
	11	1	299	305	279	239	83
	Noon		308	315	290	249	89
	Daily total (Btu/day-ft^2)		2645	2569	2226	1832	550
Jul 21	5	7					
	6	6	46	33	16	14	9
	7	5	112	99	75	52	14
	8	4	174	167	142	113	19
	9	3	227	227	204	171	52
	10	2	267	274	252	216	79
	11	1	293	303	282	246	96
	Noon		302	314	293	256	102
	Daily total (Btu/day-ft^2)		2540	2518	2235	1881	639
Aug 21	6	6	18	14	8	7	4
	7	5	85	81	69	55	12
	8	4	151	154	142	122	47
	9	3	207	219	208	185	84
	10	2	250	269	261	235	114
	11	1	278	301	294	266	133
	Noon		287	312	305	277	140
	Daily total (Btu/day-ft^2)		2266	2387	2267	2018	925
Sept 21	7	5	45	51	52	49	31
	8	4	113	130	135	129	82
	9	3	172	201	210	201	128
	10	2	218	255	267	256	163
	11	1	247	289	303	291	185
	Noon		257	301	316	303	193
	Daily total (Btu/day-ft^2)		1847	2153	2250	2157	1372
Oct 21	7	5	9	14	18	20	20
	8	4	73	99	117	122	102
	9	3	132	173	198	203	159
	10	2	178	230	260	263	200
	11	1	207	265	298	300	225
	Noon		217	277	311	313	234
	Daily total (Btu/day-ft^2)		1417	1841	2093	2131	1646
Nov 21	8	4	34	60	80	91	90
	9	3	91	138	174	188	171
	10	2	136	196	239	254	220
	11	1	164	232	278	293	248
	Noon		174	244	291	306	257
	Daily total (Btu/day-ft^2)		1023	1494	1833	1956	1712
Dec 21	8	4	20	41	58	68	72
	9	3	74	122	160	178	170
	10	2	118	181	228	247	224
	11	1	146	216	268	287	254
	Noon		155	229	281	301	263
	Daily total (Btu/day-ft^2)		871	1348	1710	1859	1702

Table 22c. 40° North Latitude

Date	AM	PM	Collector tilt angle				
			Horizontal	4/12	Latitude	Lat. + 15°	Vertical
			------Hourly clear day radiation, Btu/hr-ft^2------				
Jan 21	8	4	28	52	74	84	84
	9	3	83	131	171	185	171
	10	2	127	189	238	253	223
	11	1	155	225	278	293	253
	Noon		164	237	291	306	263
	Daily total (Btu/day-ft^2)		952	1432	1813	1935	1726
Feb 21	7	5	8	13	18	20	19
	8	4	70	98	120	125	107
	9	3	129	173	203	208	168
	10	2	175	230	266	270	211
	11	1	203	266	305	308	237
	Noon		213	278	318	320	246
	Daily total (Btu/day-ft^2)		1382	1838	2140	2181	1731
Mar 21	7	5	46	53	55	52	34
	8	4	113	133	141	135	89
	9	3	173	205	217	208	138
	10	2	218	260	276	265	176
	11	1	247	295	313	301	200
	Noon		257	306	326	313	208
	Daily total (Btu/day-ft^2)		1851	2197	2329	2235	1482
April 21	6	6	21	16	8	7	4
	7	5	88	84	70	55	11
	8	4	152	158	145	125	52
	9	3	208	223	213	190	92
	10	2	251	274	267	241	124
	11	1	278	306	301	273	145
	Noon		287	317	312	284	152
	Daily total (Btu/day-ft^2)		2285	2438	2319	2065	1009
May 21	6	6	50	35	15	14	9
	7	5	115	102	76	52	13
	8	4	176	170	144	114	24
	9	3	228	231	206	173	59
	10	2	268	278	255	219	88
	11	1	293	307	286	249	107
	Noon		302	318	297	259	113
	Daily total (Btu/day-ft^2)		2561	2565	2261	1901	711
June 21	5	7	4	3	2	2	1
	6	6	60	43	18	16	10
	7	5	123	107	77	50	14
	8	4	182	173	142	109	16
	9	3	233	231	201	165	47
	10	2	272	276	248	209	74
	11	1	296	305	278	238	92
	Noon		304	315	289	248	98
	Daily total (Btu/day-ft^2)		2645	2591	2223	1828	609
Jul 21	6	6	49	36	16	15	9
	7	5	113	101	75	52	14
	8	4	174	168	142	113	24
	9	3	225	227	203	170	58
	10	2	265	274	251	215	86
	11	1	289	303	281	244	105
	Noon		298	313	292	254	111
	Daily total (Btu/day-ft^2)		2529	2529	2229	1873	705
Aug 21	6	6	20	15	8	7	5
	7	5	86	82	68	54	12
	8	4	149	154	141	121	51
	9	3	204	217	207	184	89
	10	2	246	267	259	233	121
	11	1	272	298	292	265	141
	Noon		281	309	304	276	148
	Daily total (Btu/day-ft^2)		2234	2376	2256	2006	984
Sept 21	7	5	43	49	51	48	32
	8	4	109	127	133	127	84
	9	3	167	197	207	199	132
	10	2	211	250	265	254	168
	11	1	239	284	301	289	192
	Noon		249	295	313	301	199
	Daily total (Btu/day-ft^2)		1787	2109	2227	2135	1414
Oct 21	7	5	7	11	14	16	15
	8	4	67	93	112	117	100
	9	3	125	166	195	199	160
	10	2	169	222	256	260	203
	11	1	198	257	294	297	229
	Noon		207	269	307	310	238
	Daily total (Btu/day-ft^2)		1337	1768	2051	2087	1653
Nov 21	8	4	27	50	71	79	80
	9	3	82	128	167	181	167
	10	2	125	186	233	248	218
	11	1	153	221	273	287	248
	Noon		162	233	286	301	258
	Daily total (Btu/day-ft^2)		937	1404	1773	1890	1683
Dec 21	8	4	13	29	45	52	55
	9	3	65	111	151	168	163
	10	2	107	169	221	239	221
	11	1	134	205	262	281	252
	Noon		143	217	275	294	263
	Daily total (Btu/day-ft^2)		782	1247	1633	1773	1644

Table 22d. 42° North Latitude

			Collector tilt angle				
Date	AM	PM	Horizontal	4/12	Latitude	Lat. + 15°	Vertical
			------Hourly clear day radiation, Btu/hr-ft^2------				
Jan 21	8	4	22	42	63	71	72
	9	3	74	121	164	177	166
	10	2	117	178	231	246	221
	11	1	143	214	272	287	253
	Noon		153	226	286	300	263
	Daily total (Btu/day-ft^2)		864	1337	1746	1862	1687
Feb 21	7	5	5	9	13	14	14
	8	4	64	92	115	121	105
	9	3	121	166	199	204	169
	10	2	165	222	262	266	214
	11	1	193	257	301	304	241
	Noon		203	269	314	317	250
	Daily total (Btu/day-ft^2)		1300	1762	2096	2135	1735
Mar 21	7	5	44	51	53	51	35
	8	4	109	130	139	133	91
	9	3	167	200	215	206	142
	10	2	211	255	274	263	181
	11	1	239	289	311	299	206
	Noon		248	300	324	311	215
	Daily total (Btu/day-ft^2)		1786	2150	2306	2213	1526
April 21	6	6	23	17	8	7	5
	7	5	87	85	70	55	13
	8	4	150	157	144	124	56
	9	3	205	221	212	188	98
	10	2	246	272	265	239	132
	11	1	272	303	299	272	153
	Noon		281	314	311	283	161
	Daily total (Btu/day-ft^2)		2248	2423	2308	2053	1073
May 21	5	7	1	1	1	1	0
	6	6	53	38	16	14	9
	7	5	116	104	76	52	13
	8	4	175	171	143	114	29
	9	3	226	231	205	172	66
	10	2	265	277	254	218	96
	11	1	289	306	285	248	115
	Noon		298	316	296	258	122
	Daily total (Btu/day-ft^2)		2548	2574	2255	1894	778
June 21	5	7	8	4	4	4	2
	6	6	64	46	19	16	11
	7	5	125	110	77	50	14
	8	4	182	175	141	109	19
	9	3	231	232	201	164	54
	10	2	269	276	247	208	82
	11	1	293	305	277	237	101
	Noon		301	314	287	246	107
	Daily total (Btu/day-ft^2)		2644	2610	2220	1823	673
Jul 21	5	7	1	1	1	1	0
	6	6	52	38	17	15	10
	7	5	115	103	75	52	14
	8	4	173	169	141	112	29
	9	3	223	227	202	169	65
	10	2	261	273	250	214	94
	11	1	285	302	280	243	113
	Noon		294	311	291	253	120
	Daily total (Btu/day-ft^2)		2516	2538	2222	1866	770
Aug 21	6	6	22	17	9	8	5
	7	5	85	82	68	54	14
	8	4	147	153	140	120	55
	9	3	200	216	206	183	95
	10	2	241	265	258	232	127
	11	1	267	295	290	263	148
	Noon		275	306	302	274	156
	Daily total (Btu/day-ft^2)		2199	2362	2243	1994	1044
Sept 21	7	5	41	47	49	46	32
	8	4	105	124	131	125	86
	9	3	161	192	205	196	135
	10	2	204	245	262	252	173
	11	1	231	278	298	286	197
	Noon		240	289	311	298	206
	Daily.total (Btu/day-ft^2)		1724	2062	2203	2110	1453
Oct 21	7	5	4	7	10	11	11
	8	4	61	87	108	112	98
	9	3	117	159	190	195	161
	10	2	160	214	252	256	205
	11	1	188	249	291	293	232
	Noon		197	261	304	306	241
	Daily total (Btu/day-ft^2)		1257	1693	2006	2039	1654
Nov 21	8	4	21	40	59	67	68
	9	3	73	118	159	172	161
	10	2	115	175	227	241	216
	11	1	141	210	267	281	247
	Noon		151	222	281	295	258
	Daily total (Btu/day-ft^2)		850	1309	1705	1816	1643
Dec 21	8	4	8	18	29	34	36
	9	3	55	99	141	156	153
	10	2	96	158	213	231	216
	11	1	122	193	255	273	250
	Noon		131	205	269	287	261
	Daily total (Btu/day-ft^2)		693	1141	1545	1675	1571

Table 22e. 44° North Latitude

			Collector tilt angle				
Date	AM	PM	Horizontal	4/12	Latitude	Lat. +15°	Vertical
			------Hourly clear day radiation, Btu/hr-ft^2------				
Jan 21	8	4	15	32	50	56	58
	9	3	65	110	155	168	159
	10	2	106	167	224	239	218
	11	1	132	202	266	280	251
	Noon		141	214	280	294	262
	Daily total (Btu/day-ft^2)		776	1237	1669	1778	1633
Feb 21	7	5	3	6	8	9	9
	8	4	58	86	110	115	102
	9	3	113	158	195	200	169
	10	2	156	214	258	262	215
	11	1	183	248	297	300	244
	Noon		192	260	311	313	254
	Daily total (Btu/day-ft^2)		1217	1683	2049	2085	1733
Mar 21	7	5	42	49	52	49	35
	8	4	105	127	136	131	93
	9	3	160	195	212	204	146
	10	2	203	249	271	261	186
	11	1	230	283	308	296	212
	Noon		239	294	321	309	221
	Daily total (Btu/day-ft^2)		1719	2099	2282	2189	1565
April 21	6	6	24	19	8	7	5
	7	5	87	85	69	55	16
	8	4	148	156	143	123	60
	9	3	201	219	211	187	103
	10	2	241	269	264	238	138
	11	1	266	300	298	270	161
	Noon		275	310	309	281	169
	Daily total (Btu/day-ft^2)		2209	2405	2295	2040	1135
May 21	5	7	3	2	2	2	1
	6	6	56	41	16	14	9
	7	5	117	106	75	51	13
	8	4	174	172	143	113	34
	9	3	223	231	204	171	72
	10	2	261	276	253	217	103
	11	1	285	305	284	246	124
	Noon		293	315	294	257	131
	Daily total (Btu/day-ft^2)		2532	2580	2248	1886	844
June 21	5	7	12	6	6	5	3
	6	6	67	49	19	17	11
	7	5	127	112	77	49	15
	8	4	182	176	141	108	24
	9	3	230	232	200	164	60
	10	2	266	276	246	207	90
	11	1	289	304	276	236	109
	Noon		297	313	286	245	116
	Daily total (Btu/day-ft^2)		2640	2625	2215	1817	741
Jul 21	5	7	3	2	2	2	1
	6	6	55	41	17	15	10
	7	5	116	105	75	51	14
	8	4	172	170	141	112	34
	9	3	221	227	201	168	71
	10	2	258	272	248	213	102
	11	1	281	300	279	242	121
	Noon		289	310	289	252	128
	Daily total (Btu/day-ft^2)		2502	2545	2215	1858	834
Aug 21	6	6	23	18	9	8	5
	7	5	85	83	68	53	16
	8	4	145	152	139	119	58
	9	3	196	214	204	181	100
	10	2	236	262	256	230	134
	11	1	261	292	289	261	156
	Noon		269	302	300	272	163
	Daily total (Btu/day-ft^2)		2161	2344	2229	1980	1103
Sept 21	7	5	39	45	47	45	32
	8	4	101	120	129	123	88
	9	3	155	187	202	194	138
	10	2	196	239	260	249	178
	11	1	223	272	296	284	203
	Noon		232	283	308	296	211
	Daily total (Btu/day-ft^2)		1658	2011	2176	2084	1488
Oct 21	7	5	2	4	6	7	6
	8	4	55	80	102	107	95
	9	3	109	152	186	190	160
	10	2	151	206	248	251	207
	11	1	177	240	286	289	235
	Noon		187	251	300	302	244
	Daily total (Btu/day-ft^2)		1176	1615	1957	1988	1649
Nov 21	8	4	15	30	47	52	54
	9	3	64	107	150	162	154
	10	2	104	164	219	233	213
	11	1	130	199	261	274	246
	Noon		139	210	274	288	256
	Daily total (Btu/day-ft^2)		763	1210	1627	1732	1588
Dec 21	8	4	3	8	14	16	17
	9	3	46	87	129	143	142
	10	2	85	145	204	221	209
	11	1	110	180	247	264	245
	Noon		119	192	261	279	257
	Daily total (Btu/day-ft^2)		607	1032	1447	1567	1484

Table 22f. 46° North Latitude

			Collector tilt angle				
Date	AM	PM	Horizontal	4/12	Latitude	Lat. + 15°	Vertical
			------Hourly clear day radiation, Btu/hr-ft²------				
Jan 21	8	4	9	21	35	40	41
	9	3	56	99	145	157	151
	10	2	95	155	216	230	213
	11	1	120	190	258	272	248
	Noon		128	202	273	286	259
	Daily total (Btu/day-ft²)		688	1133	1582	1683	1565
Feb 21	7	5	1	3	4	5	5
	8	4	52	79	105	109	99
	9	3	105	150	190	195	168
	10	2	146	205	254	257	217
	11	1	172	239	293	296	246
	Noon		181	250	306	309	256
	Daily total (Btu/day-ft²)		1133	1601	1998	2032	1724
Mar 21	7	5	39	47	50	47	35
	8	4	100	123	134	128	95
	9	3	154	190	210	201	149
	10	2	195	243	269	258	191
	11	1	221	276	306	294	218
	Noon		230	287	318	306	227
	Daily total (Btu/day-ft²)		1649	2044	2255	2163	1600
April 21	6	6	26	20	9	8	5
	7	5	87	85	69	54	18
	8	4	146	155	142	122	64
	9	3	196	217	209	186	109
	10	2	235	265	262	236	145
	11	1	260	296	296	268	168
	Noon		268	306	307	279	176
	Daily total (Btu/day-ft²)		2167	2384	2281	2027	1195
May 21	5	7	6	4	3	3	2
	6	6	59	44	16	14	10
	7	5	118	108	75	51	13
	8	4	173	173	142	113	39
	9	3	221	230	203	170	79
	10	2	257	275	252	216	111
	11	1	280	303	282	245	132
	Noon		288	313	293	255	139
	Daily total (Btu/day-ft²)		2515	2584	2241	1878	909
June 21	5	7	16	8	7	6	4
	6	6	71	53	19	17	11
	7	5	128	115	77	49	15
	8	4	181	177	140	108	29
	9	3	227	232	199	163	67
	10	2	263	275	245	206	98
	11	1	285	302	275	234	118
	Noon		292	312	285	244	124
	Daily total (Btu/day-ft²)		2634	2637	2209	1811	808
Jul 21	5	7	6	4	3	3	2
	6	6	58	44	17	15	10
	7	5	117	107	75	51	14
	8	4	171	170	140	111	39
	9	3	218	227	200	167	77
	10	2	254	270	247	212	109
	11	1	276	298	277	240	129
	Noon		284	308	288	250	136
	Daily total (Btu/day-ft²)		2486	2549	2208	1849	897
Aug 21	6	6	25	20	9	8	6
	7	5	85	83	67	53	18
	8	4	143	151	138	118	62
	9	3	192	211	203	180	105
	10	2	230	258	254	228	140
	11	1	254	288	287	260	163
	Noon		262	298	298	270	170
	Daily total (Btu/day-ft²)		2120	2322	2214	1964	1158
Sept 21	7	5	37	43	46	43	31
	8	4	96	117	126	121	89
	9	3	148	182	200	191	141
	10	2	189	233	257	246	182
	11	1	214	265	293	281	208
	Noon		223	276	305	293	216
	Daily total (Btu/day-ft²)		1590	1957	2147	2056	1518
Oct 21	7	5	1	2	3	3	3
	8	4	49	73	97	101	91
	9	3	101	144	181	185	159
	10	2	141	197	243	246	207
	11	1	167	230	282	284	236
	Noon		176	242	295	297	246
	Daily total (Btu/day-ft²)		1094	1534	1905	1934	1638
Nov 21	8	4	9	20	32	36	37
	9	3	54	96	140	151	145
	10	2	93	152	211	224	208
	11	1	118	187	253	266	242
	Noon		127	198	267	280	254
	Daily total (Btu/day-ft²)		676	1107	1539	1636	1519
Dec 21	8	4	0	1	2	3	3
	9	3	36	73	115	127	127
	10	2	74	132	193	209	201
	11	1	98	167	237	254	239
	Noon		106	179	252	269	252
	Daily total (Btu/day-ft²)		524	925	1347	1455	1392

Table 22g. 48° North Latitude

			Collector tilt angle				
Date	**AM**	**PM**	**Horizontal**	**4/12**	**Latitude**	**Lat. + 15°**	**Vertical**
			------Hourly clear day radiation, Btu/hr-ft^2------				
Jan 21	8	4	5	11	20	22	233
	9	3	46	87	133	144	140
	10	2	84	143	207	220	207
	11	1	108	177	250	263	243
	Noon		116	189	264	278	255
	Daily total (Btu/day-ft^2)		602	1026	1483	1576	1481
Feb 21	7	5	0	1	1	2	2
	8	4	46	72	98	103	94
	9	3	96	142	185	189	166
	10	2	136	195	249	252	217
	11	1	161	229	288	291	248
	Noon		170	240	302	304	258
	Daily total (Btu/day-ft^2)		1049	1518	1945	1977	1710
Mar 21	7	5	37	45	48	46	35
	8	4	95	119	132	126	96
	9	3	147	185	207	198	152
	10	2	187	236	266	255	195
	11	1	212	269	303	291	222
	Noon		220	280	315	303	232
	Daily total (Btu/day-ft^2)		1577	1986	2226	2135	1631
April 21	6	6	28	22	9	8	5
	7	5	86	86	69	54	20
	8	4	143	154	141	121	68
	9	3	192	214	208	184	114
	10	2	229	262	260	234	151
	11	1	253	292	294	266	175
	Noon		261	302	305	277	184
	Daily total (Btu/day-ft^2)		2121	2359	2265	2012	1252
May 21	5	7	9	5	4	4	3
	6	6	62	47	16	14	10
	7	5	119	110	75	51	13
	8	4	172	173	141	112	44
	9	3	218	229	202	169	85
	10	2	253	273	250	214	118
	11	1	275	300	281	244	140
	Noon		282	310	291	254	147
	Daily total (Btu/day-ft^2)		2496	2584	2233	1869	972
June 21	5	7	21	10	9	7	5
	6	6	74	56	19	17	11
	7	5	129	117	77	49	15
	8	4	181	178	140	107	35
	9	3	225	232	198	162	74
	10	2	259	274	244	205	105
	11	1	280	301	273	233	126
	Noon		287	310	283	242	133
	Daily total (Btu/day-ft^2)		2624	2646	2203	1803	874
Jul 21	5	7	10	5	5	4	3
	6	6	61	47	18	15	11
	7	5	117	109	75	51	14
	8	4	170	171	139	110	43
	9	3	215	226	199	166	83
	10	2	250	269	246	210	116
	11	1	271	296	276	239	137
	Noon		279	305	286	249	144
	Daily total (Btu/day-ft^2)		2467	2549	2199	1840	959
Aug 21	6	6	27	21	10	8	6
	7	5	84	83	67	53	20
	8	4	140	150	137	117	66
	9	3	188	209	201	178	110
	10	2	224	255	252	226	146
	11	1	247	284	285	257	169
	Noon		255	294	296	268	177
	Daily total (Btu/day-ft^2)		2076	2297	2197	1948	1212
Sept 21	7	5	35	41	44	41	31
	8	4	92	113	124	118	90
	9	3	142	177	197	188	143
	10	2	181	227	253	243	185
	11	1	205	258	289	278	212
	Noon		213	269	302	289	221
	Daily total (Btu/day-ft^2)		1520	1899	2116	2025	1544
Oct 21	7	5	0	0	1	1	1
	8	4	43	66	90	94	86
	9	3	93	135	175	179	157
	10	2	132	188	238	241	207
	11	1	156	221	277	279	237
	Noon		165	232	290	292	247
	Daily total (Btu/day-ft^2)		1012	1452	1850	1878	1622
Nov 21	8	4	4	10	18	20	21
	9	3	45	84	128	138	134
	10	2	82	140	201	214	201
	11	1	106	174	244	257	238
	Noon		114	185	259	271	249
	Daily total (Btu/day-ft^2)		591	1000	1440	1529	1435
Dec 21	9	3	27	59	97	108	109
	10	2	63	118	180	195	189
	11	1	86	153	226	243	231
	Noon		94	164	241	258	244
	Daily total (Btu/day-ft^2)		446	824	1249	1349	1303

Table 23. Average solar radiation.

Data are the averages of observations in all weather conditions over a number of years. Values include direct + diffuse + reflected radiation, Btu/day-ft^2, on south-facing surfaces. (Average snow covers included in the ground reflectance calculation.) Developed by MWPS with the Liu and Jordan technique and horizontal radiation data from ASHRAE GRP170. Measure collector tilt angles from horizontal. Surfaces with a latitude + 15° tilt angle usually receive the most energy during the grain drying and space heating seasons. Use data from the nearest station, Fig 41.

Example: Find the 24-hr average temperature rise from a 2400-ft^2 solar collector on a south-facing 4/12 roof slope in Oct. and Nov. near Bismarck, ND. Airflow is 10,000 cfm.

Answer: Average daily solar radiation on a 4/12 slope in Oct. and Nov. (Table 23a):

$$\frac{1321 + 893}{2} = 1107 \text{ Btu/day-ft}^2$$

The collector plan in this handbook gives an average all day efficiency of 40% for a 4/12 roof slope collector.

24-hr average temperature rise

$$= \frac{\text{Collector area} \times \text{Avg. solar energy} \times \text{Avg. collector efficiency}}{1.1 \times \text{Collector airflow} \times 24\text{hr/day}}$$

$$= \frac{2400 \text{ ft}^2 \times 1107 \text{ Btu/day-ft}^2 \times 0.40}{1.1 \times 10{,}000 \text{ cfm} \times 24 \text{ hr/day}} = \textbf{about 4F}$$

Table 23a. Bismarck, ND (46.8° North Latitude)

	Collector tilt angle				
Month	Horizontal (0°)	4/12 (18°)	Latitude (47°)	Lat. +15° (62°)	Vertical (90°)
	------Average total daily radiation, Btu/day-ft²------				
January	587	1004	1487	1631	1649
February	934	1377	1851	1965	1891
March	1328	1673	1955	1961	1704
April	1668	1841	1844	1714	1260
May	2056	2105	1905	1671	1067
June	2174	2143	1848	1581	957
July	2306	2289	1987	1702	1024
August	1929	2014	1866	1658	1085
September	1441	1643	1698	1596	1188
October	1018	1321	1567	1572	1344
November	600	893	1196	1263	1192
December	464	798	1187	1303	1319

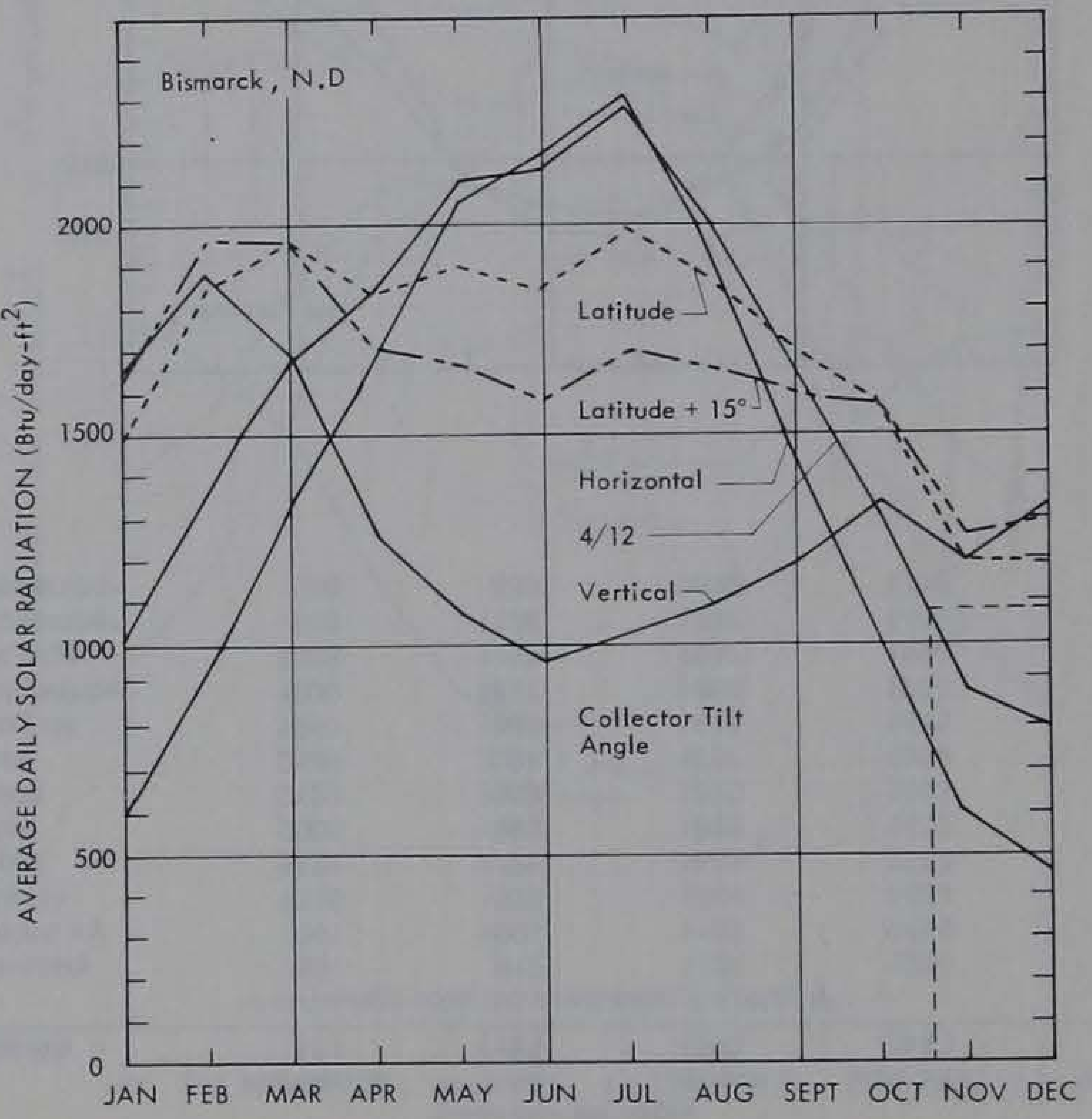


Table 23b. Cleveland, OH (41.4°North Latitude)

	Collector tilt angle				
Month	Horizontal (0°)	4/12 (18°)	Latitude (41°)	Lat. + 15° (56°)	Vertical (90°)
	------Average total daily radiation, Btu/day-ft^2------				
January	467	639	795	849	819
February	682	860	1004	1040	948
March	1207	1424	1547	1530	1225
April	1444	1537	1499	1383	915
May	1928	1937	1767	1557	896
June	2103	2042	1794	1540	828
July	2094	2046	1808	1558	842
August	1841	1880	1747	1556	920
September	1410	1552	1563	1468	1010
October	997	1207	1335	1330	1068
November	527	673	787	812	721
December	427	598	751	804	771

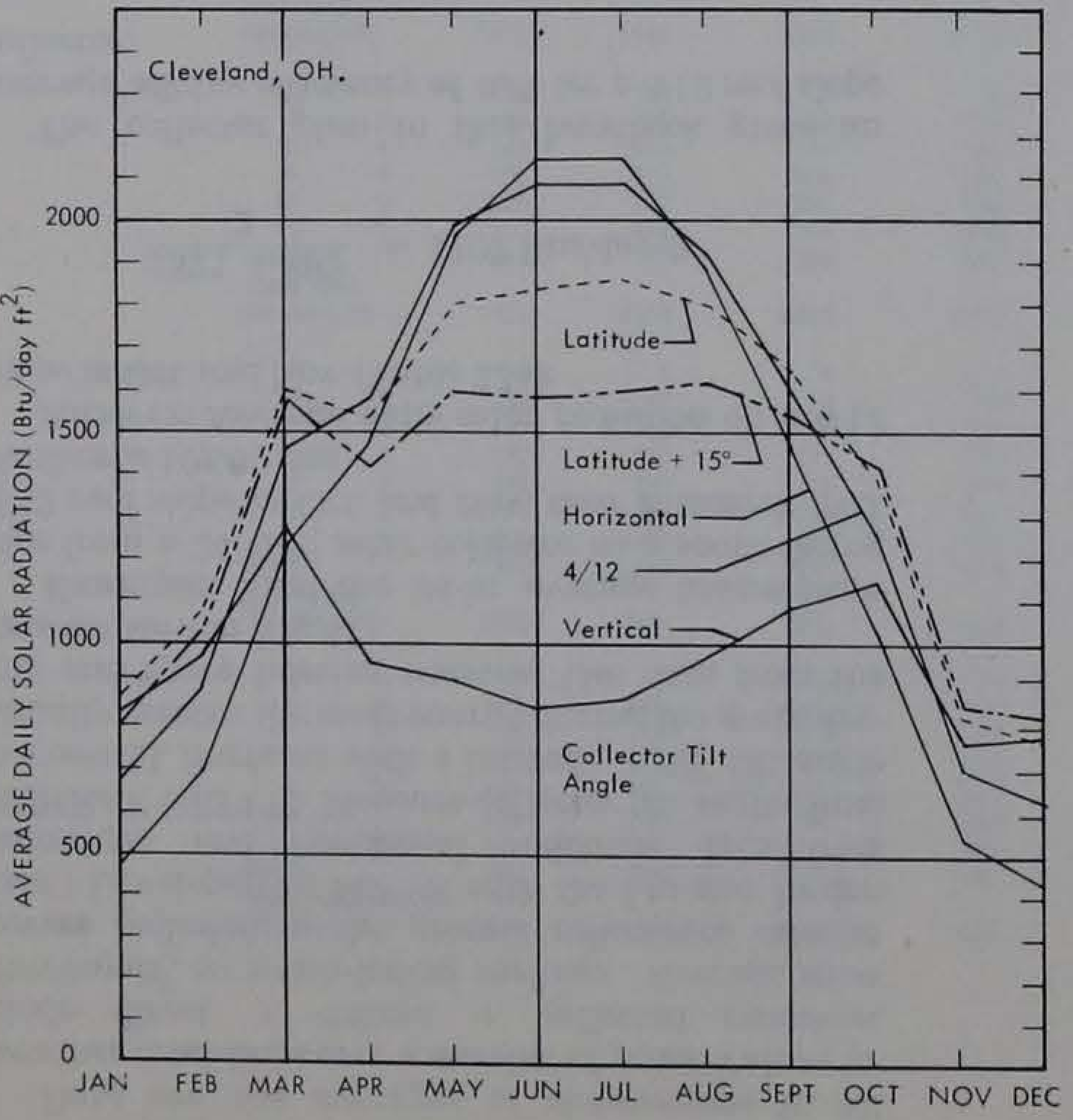


Table 23c. Columbia, MO (39.0°North Latitude)

	Collector tilt angle				
Month	Horizontal (0°)	4/12 (18°)	Latitude (39°)	Lat. + 15° (54°)	Vertical (90°)
	------Average total daily radiation, Btu/day-ft^2------				
January	651	912	1124	1210	1153
February	941	1209	1402	1459	1288
March	1316	1536	1644	1624	1252
April	1631	1729	1689	1563	988
May	2000	1993	1829	1612	873
June	2129	2053	1820	1563	788
July	2149	2084	1857	1599	807
August	1953	1981	1846	1645	914
September	1690	1857	1869	1762	1158
October	1203	1455	1597	1598	1256
November	840	1126	1337	1405	1249
December	590	839	1039	1119	1056

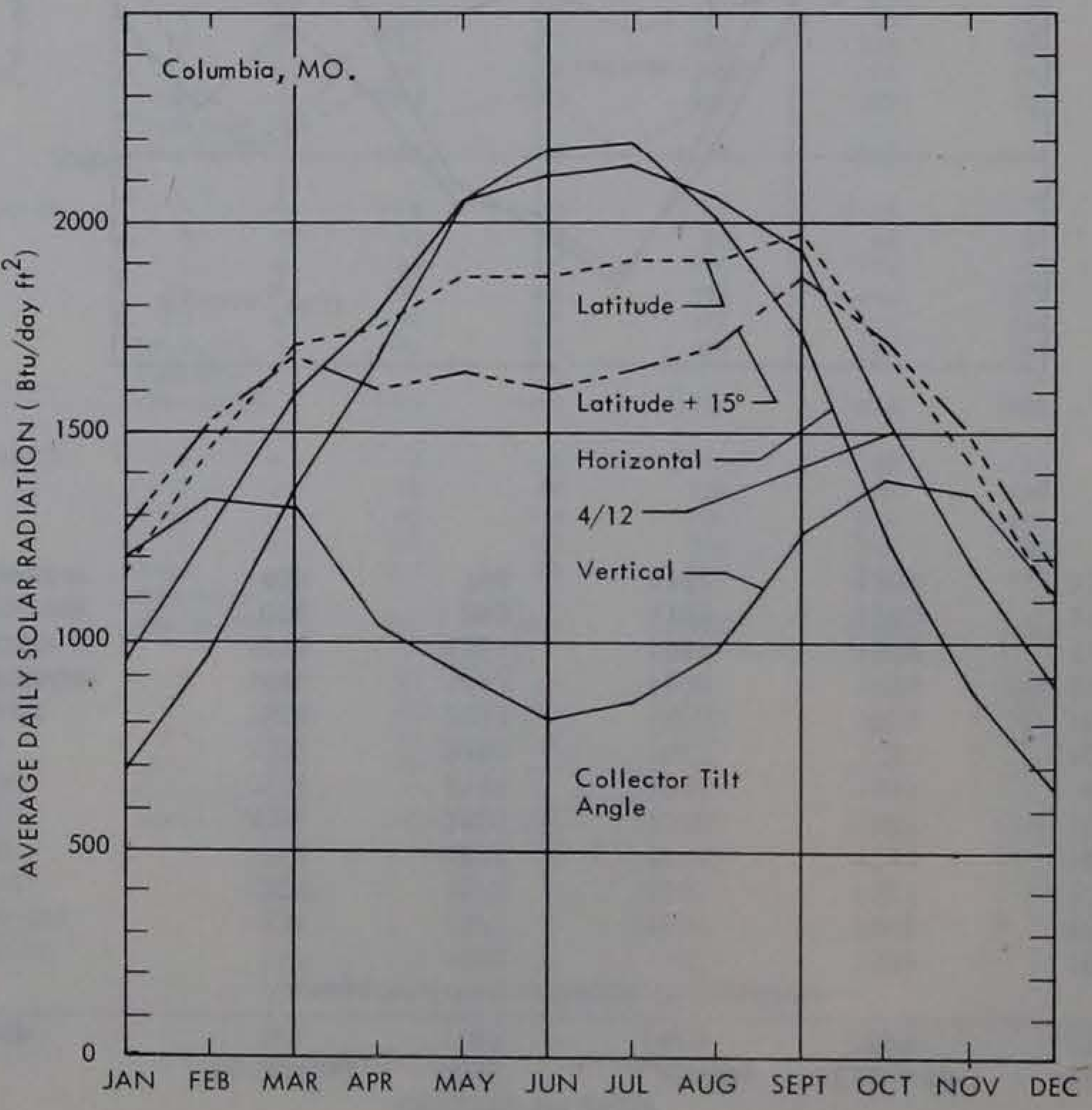


Table 23d. Columbus, OH (40.0°North Latitude)

	Collector tilt angle				
Month	Horizontal (0°)	4/12 (18°)	Latitude (40°)	Lat. + 15° (55°)	Vertical (90°)
	------Average total daily radiation, Btu/day-ft²------				
January	486	651	788	838	791
February	747	936	1073	1106	972
March	1113	1285	1368	1343	1040
April	1481	1569	1528	1411	909
May	1839	1838	1683	1485	837
June	2111	2042	1804	1549	803
July	2041	1986	1766	1524	801
August	1573	1593	1482	1324	779
September	1189	1284	1277	1197	811
October	920	1088	1180	1170	922
November	479	584	656	667	572
December	430	581	703	744	686

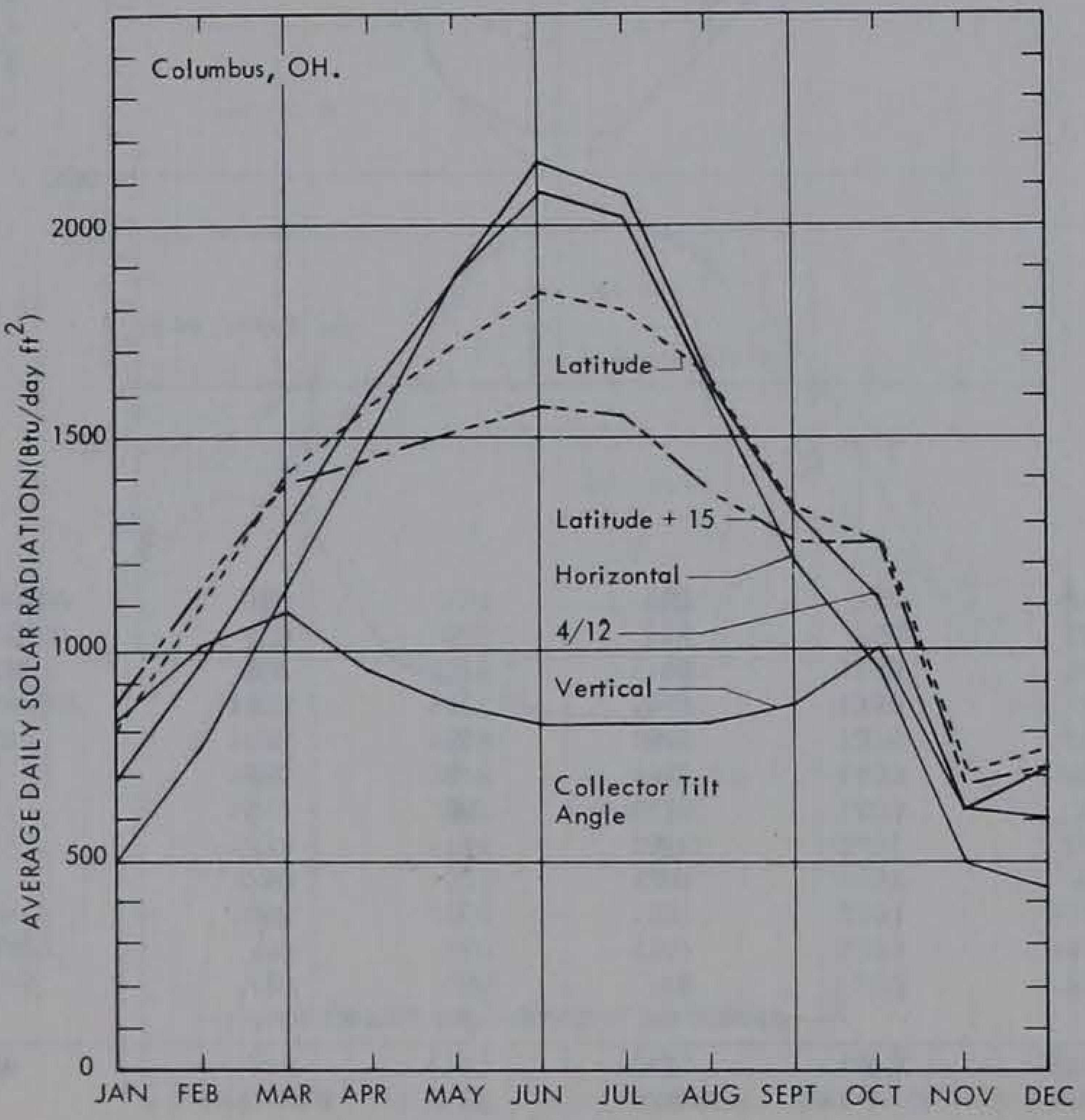


Table 23e. Dodge City, KA (37.8°North Latitude)

	Collector tilt angle				
Month	Horizontal (0°)	4/12 (18°)	Latitude (38°)	Lat. + 15° (53°)	Vertical (90°)
	------Average total daily radiation, Btu/day-ft²------				
January	953	1404	1753	1910	1815
February	1186	1552	1803	1885	1645
March	1566	1842	1976	1961	1492
April	1976	2103	2062	1910	1161
May	2127	2113	1943	1710	887
June	2460	2359	2092	1784	826
July	2401	2317	2067	1772	834
August	2211	2238	2090	1859	978
September	1842	2023	2037	1922	1231
October	1421	1736	1910	1922	1500
November	1065	1461	1743	1849	1647
December	874	1316	1659	1815	1729

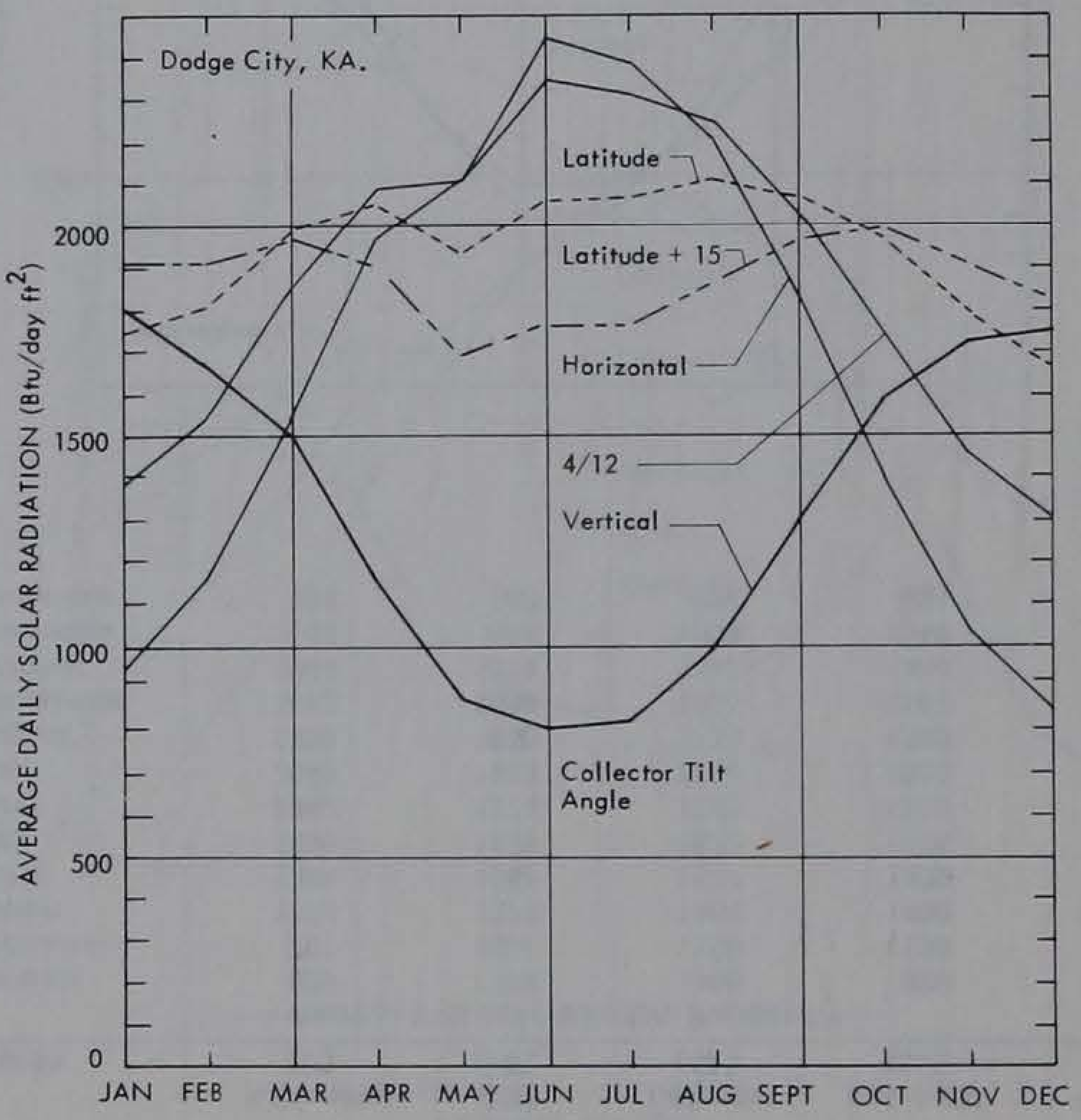


Table 23f. East Lansing, MI (42.7°North Latitude)

Month	Horizontal (0°)	Collector tilt angle 4/12 (18°)	Latitude (43°)	Lat. + 15° (58°)	Vertical (90°)
	------Average total daily radiation, Btu/day-ft²------				
January	426	590	748	802	787
February	739	966	1167	1221	1139
March	1086	1280	1397	1381	1129
April	1250	1327	1294	1197	830
May	1733	1744	1588	1401	843
June	1914	1867	1636	1409	799
July	1885	1848	1630	1409	804
August	1628	1665	1543	1376	849
September	1303	1437	1447	1358	955
October	892	1079	1198	1189	966
November	473	606	714	735	656
December	380	534	683	734	719

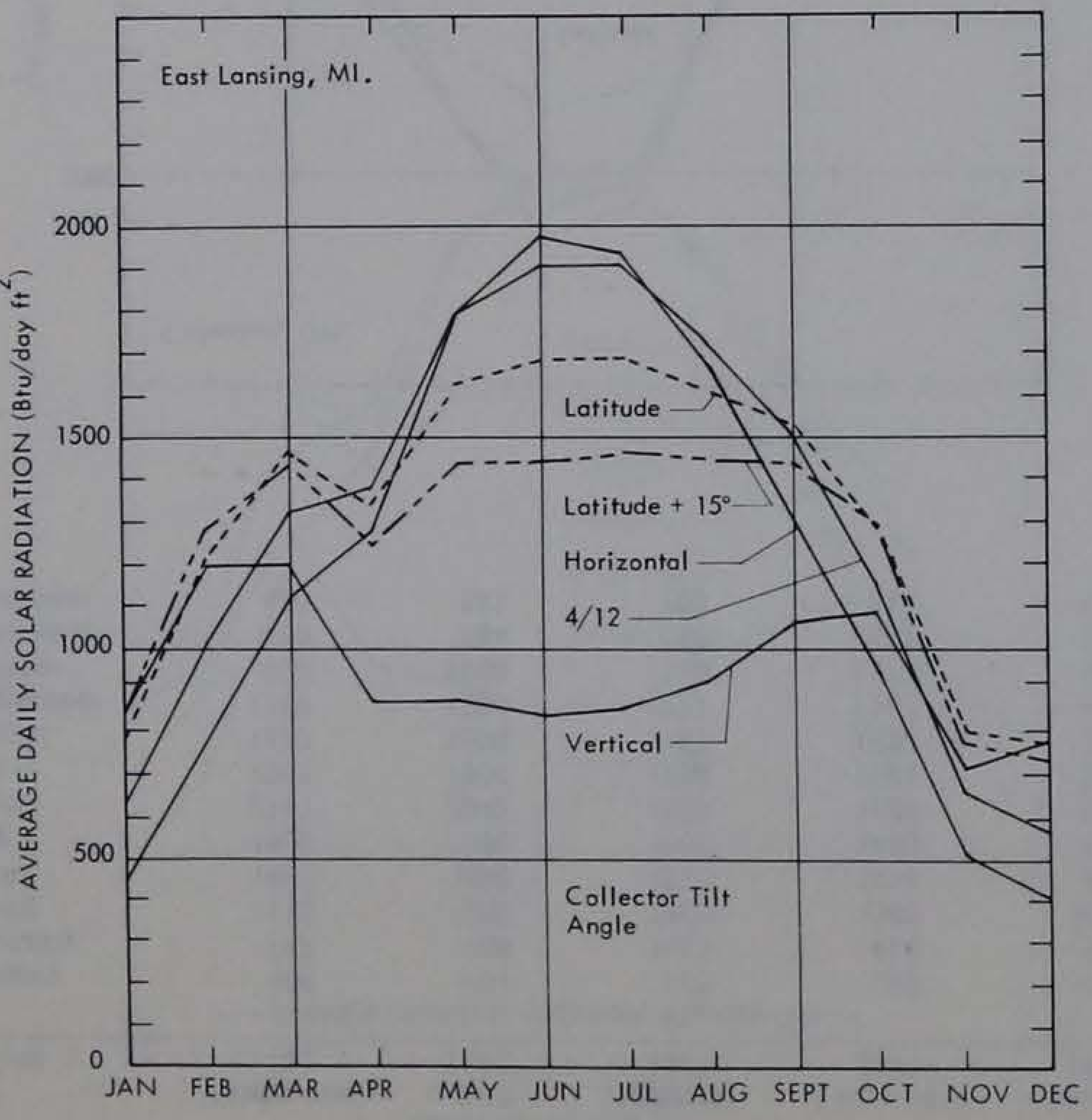


Table 23g. Indianapolis, IN (39.7°North Latitude)

Month	Horizontal (0°)	Collector tilt angle 4/12 (18°)	Latitude (40°)	Lat. + 15° (55°)	Vertical (90°)
	------Average total daily radiation, Btu/day-ft²------				
January	526	714	868	926	876
February	797	1007	1159	1198	1055
March	1184	1373	1464	1438	1105
April	1481	1567	1527	1409	904
May	1828	1825	1672	1476	828
June	2042	1974	1747	1503	781
July	2040	1983	1764	1523	796
August	1832	1860	1732	1545	882
September	1513	1658	1665	1567	1048
October	1094	1319	1447	1444	1141
November	662	861	1009	1049	925
December	491	680	834	891	834

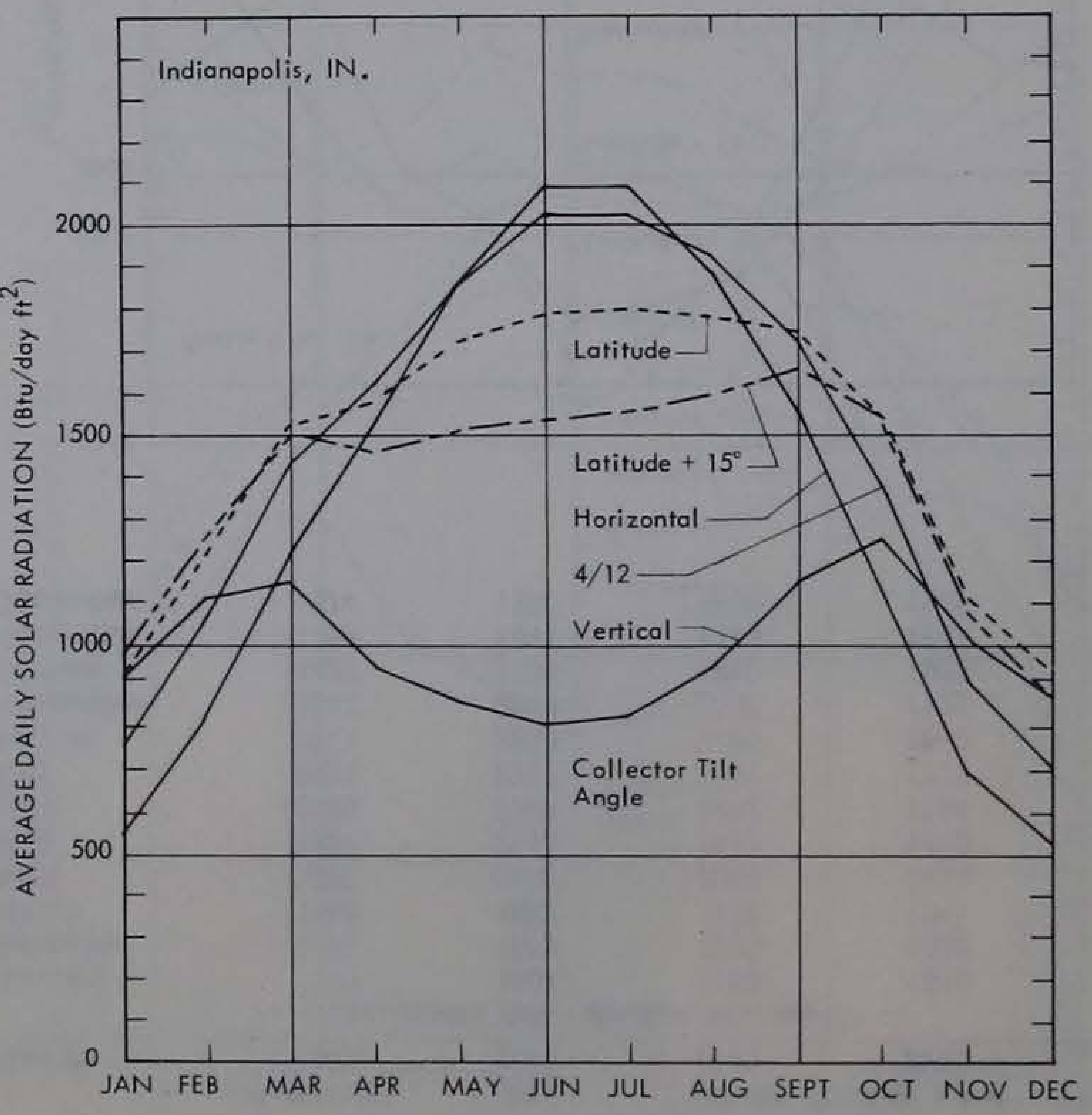


Table 23h. Lemont, IL (41.7°North Latitude)

Month	Collector tilt angle Horizontal (0°)	4/12 (18°)	Latitude (42°)	Lat. + 15° (57°)	Vertical (90°)
	------Average total daily radiation, Btu/day-ft²------				
January	590	862	1115	1207	1181
February	879	1162	1398	1461	1332
March	1256	1490	1623	1602	1271
April	1482	1581	1545	1428	953
May	1866	1875	1710	1507	877
June	2042	1985	1744	1499	817
July	1991	1947	1721	1486	818
August	1837	1878	1744	1554	924
September	1469	1624	1640	1542	1064
October	1016	1237	1375	1370	1105
November	639	856	1033	1077	967
December	531	790	1030	1115	1081

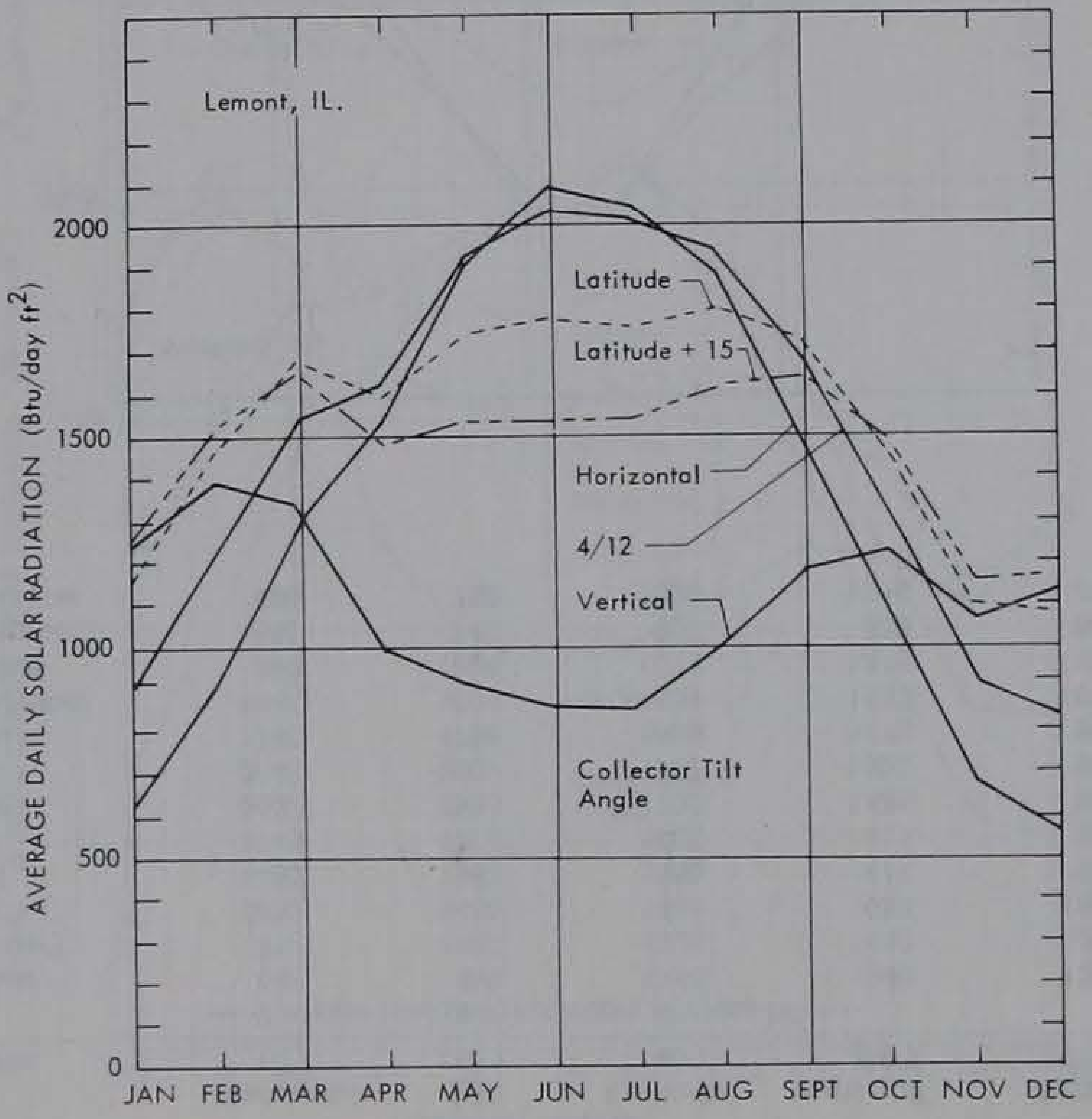


Table 23i. Lincoln, NE (40.9°North Latitude)

Month	Collector tilt angle Horizontal (0°)	4/12 (18°)	Latitude (41°)	Lat. + 15° (56°)	Vertical (90°)
	------Average total daily radiation, Btu/day-ft²------				
January	713	1064	1385	1512	1493
February	956	1266	1515	1585	1437
March	1300	1539	1673	1657	1316
April	1588	1694	1657	1530	998
May	1856	1860	1699	1499	858
June	2041	1979	1744	1500	801
July	2011	1962	1739	1501	809
August	1903	1941	1805	1608	935
September	1544	1704	1719	1618	1101
October	1216	1503	1683	1688	1357
November	773	1058	1288	1354	1220
December	643	978	1277	1390	1346

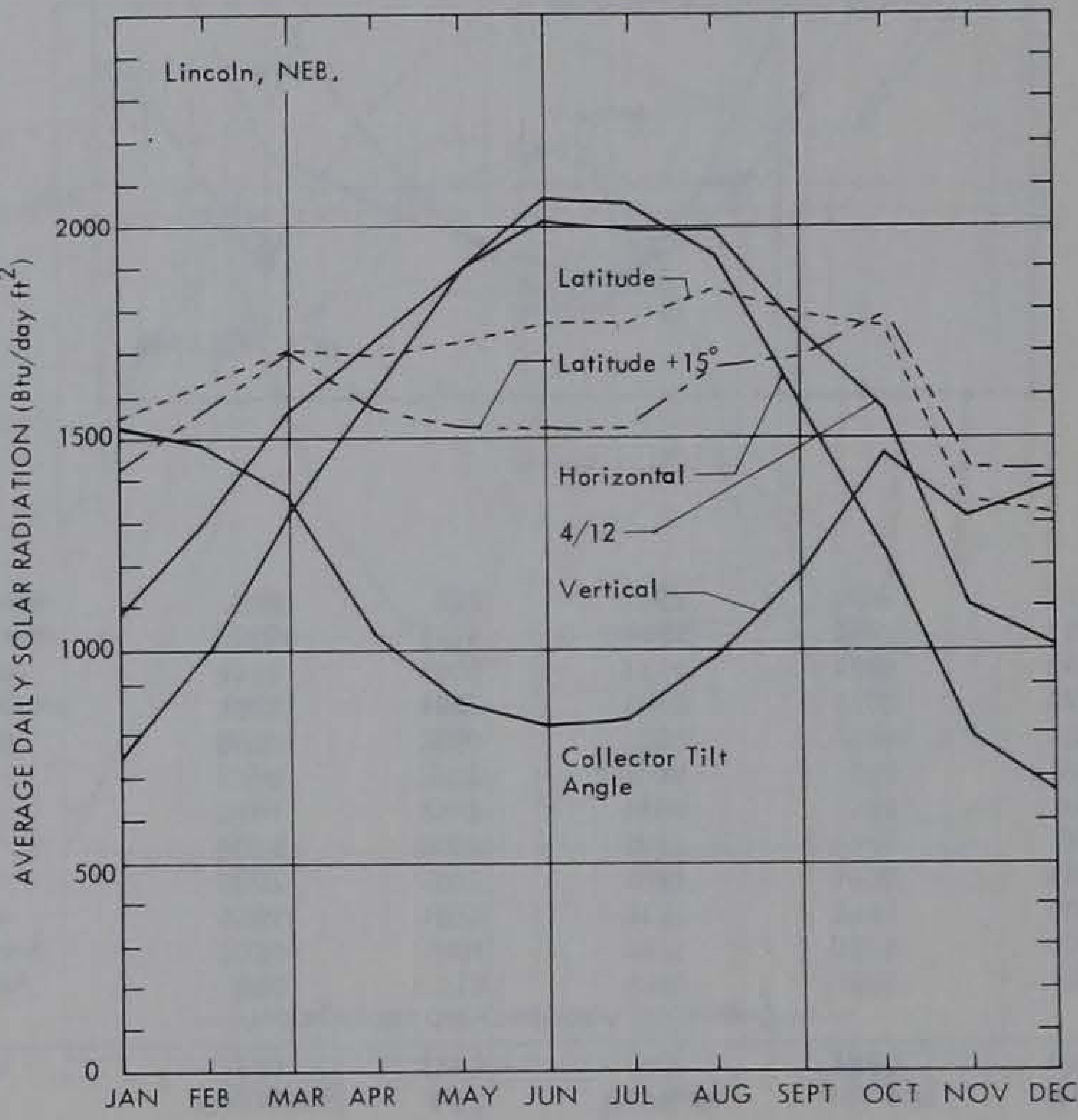
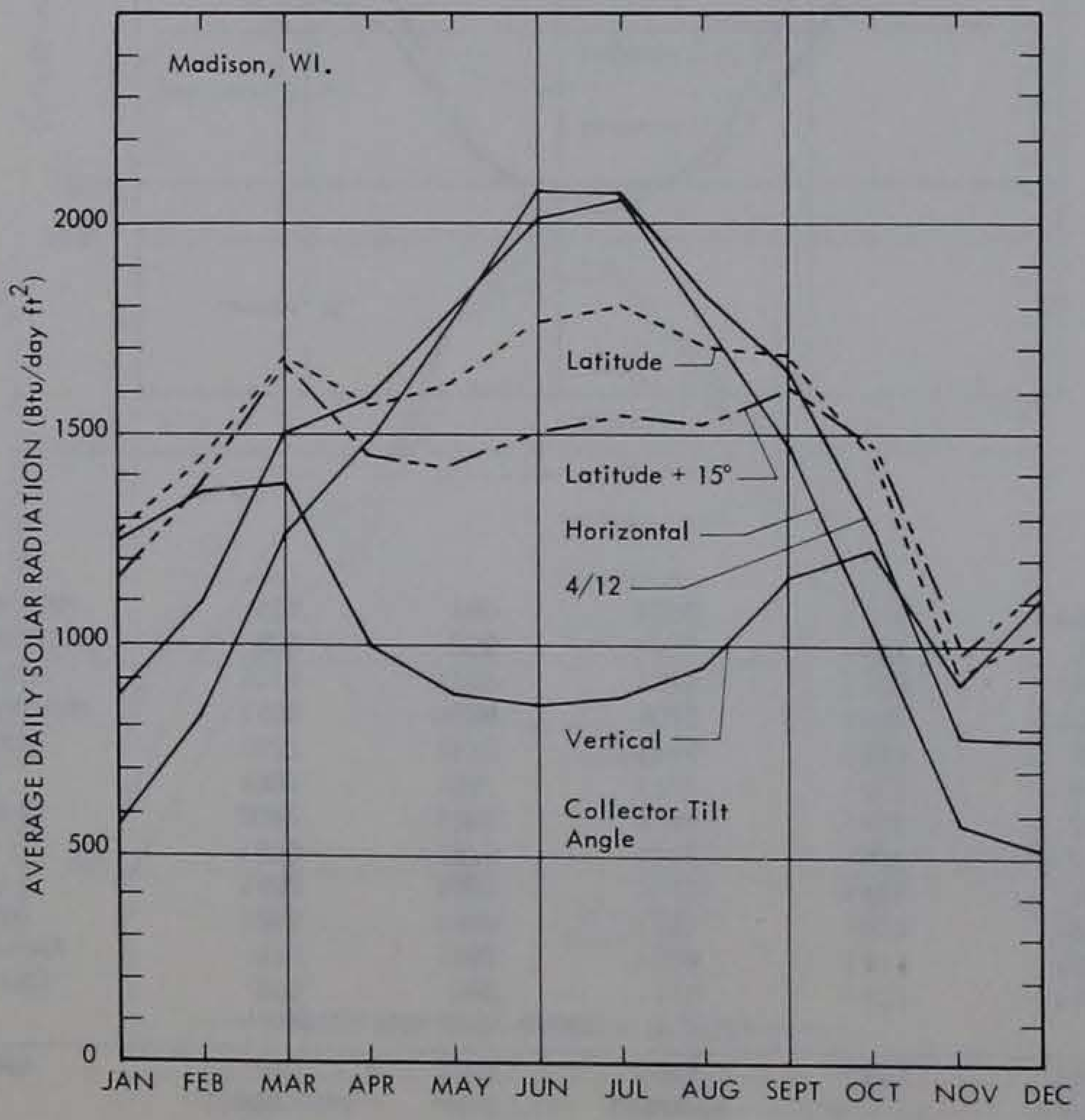


Table 23j. Madison, WI (43.1°North Latitude)

Month	Collector tilt angle Horizontal (0°)	4/12 (18°)	Latitude (43°)	Lat. + 15° (58°)	Vertical (90°)
	------Average total daily radiation, Btu/day-ft²------				
January	565	856	1146	1246	1235
February	812	1087	1339	1410	1331
March	1232	1480	1641	1632	1349
April	1455	1562	1533	1418	979
May	1745	1759	1600	1411	855
June	2032	1983	1733	1489	840
July	2047	2009	1767	1522	861
August	1740	1786	1655	1475	909
September	1444	1608	1631	1533	1082
October	993	1224	1379	1375	1125
November	556	743	903	938	847
December	496	758	1020	1110	1099

Table 23k. Rapid City, SD (44.2°North Latitude)

Month	Collector tilt angle Horizontal (0°)	4/12 (18°)	Latitude (44°)	Lat. + 15° (59°)	Vertical (90°)
	------Average total daily radiation, Btu/day-ft²------				
January	688	1112	1550	1692	1674
February	1033	1464	1871	1974	1844
March	1504	1871	2137	2141	1801
April	1807	1977	1967	1828	1284
May	2028	2057	1867	1641	994
June	2194	2147	1866	1598	909
July	2236	2202	1926	1654	940
August	2020	2090	1939	1724	1065
September	1628	1842	1892	1782	1274
October	1179	1509	1754	1765	1479
November	763	1115	1448	1534	1434
December	590	972	1367	1495	1479



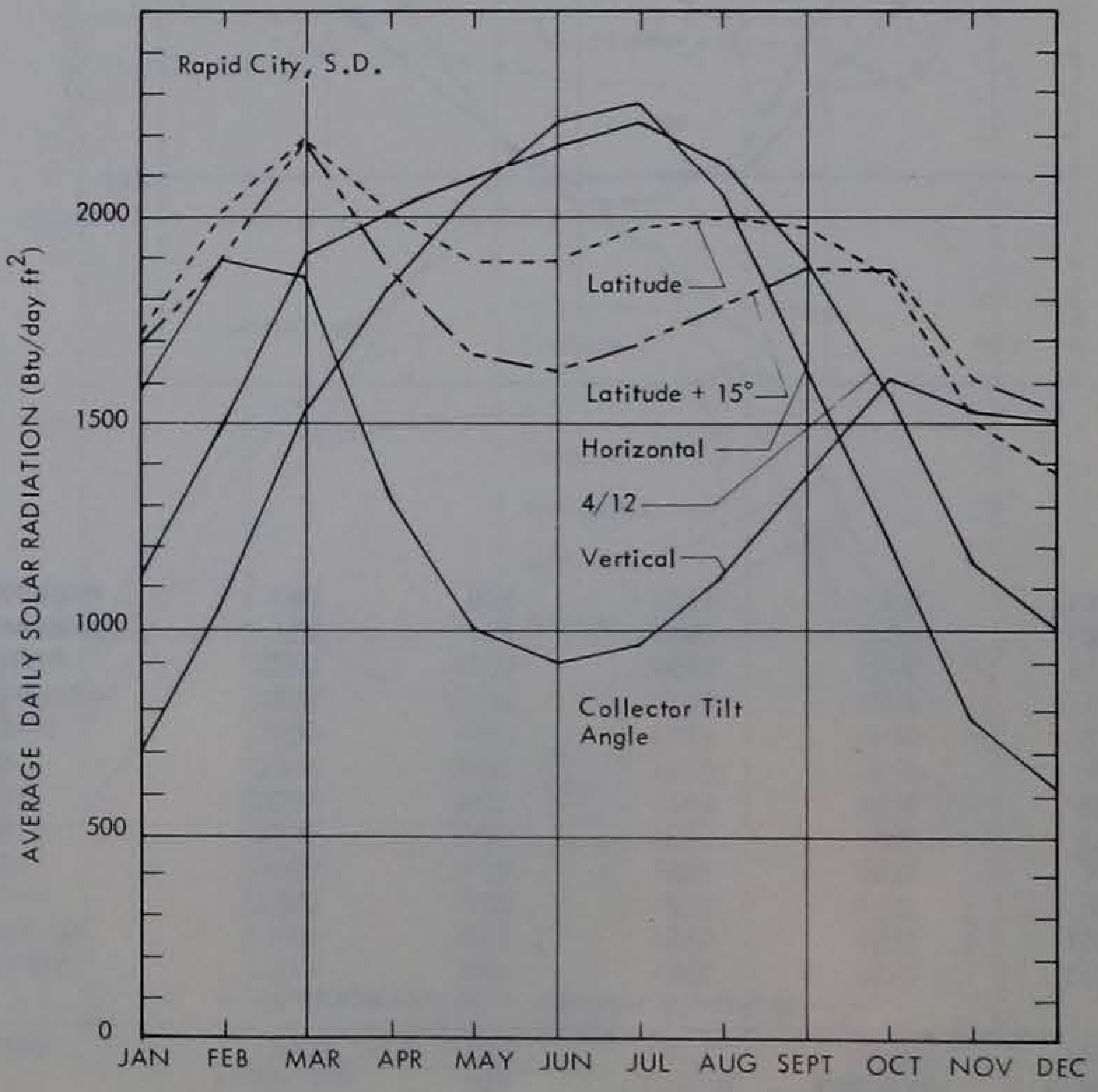
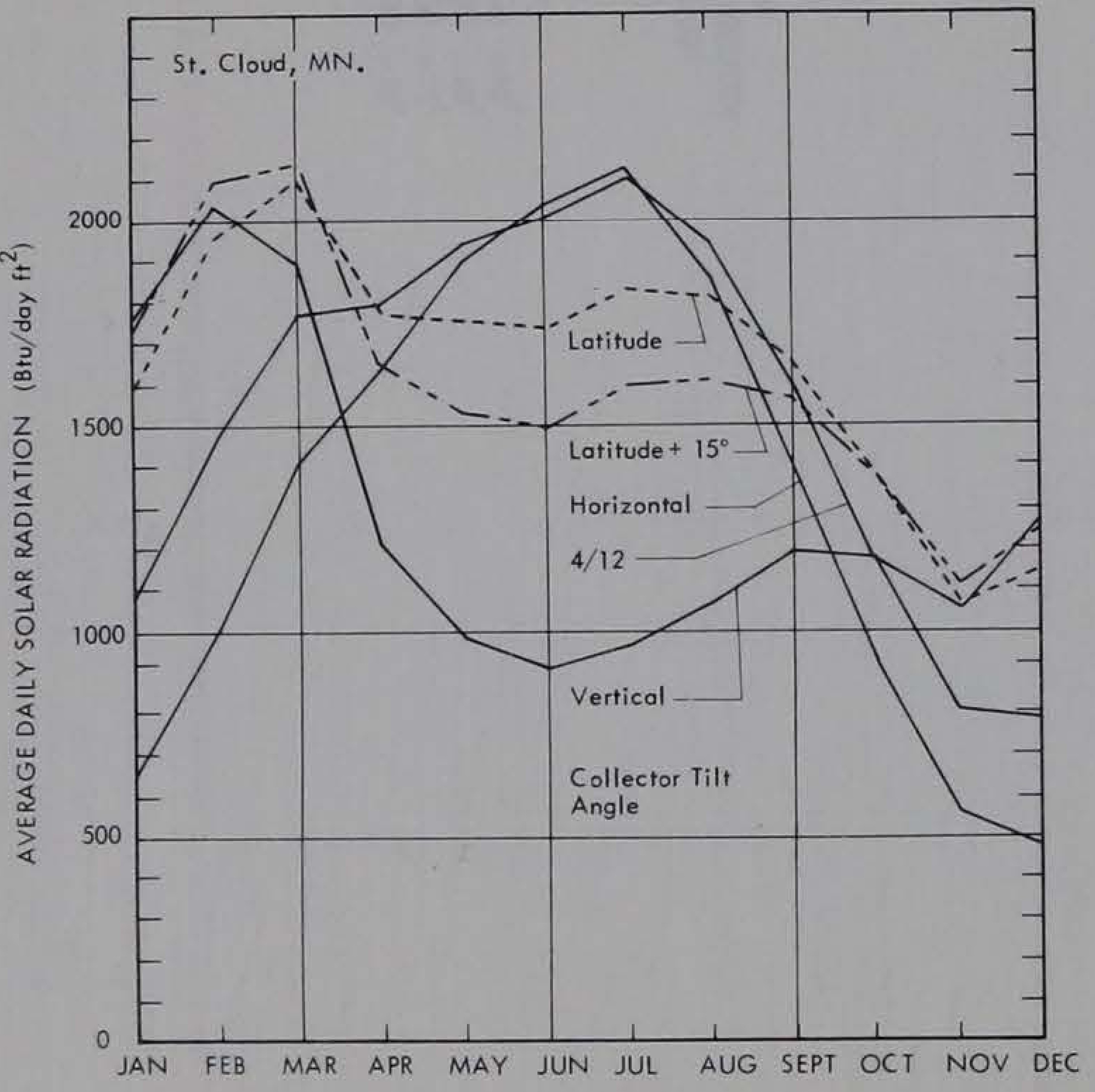


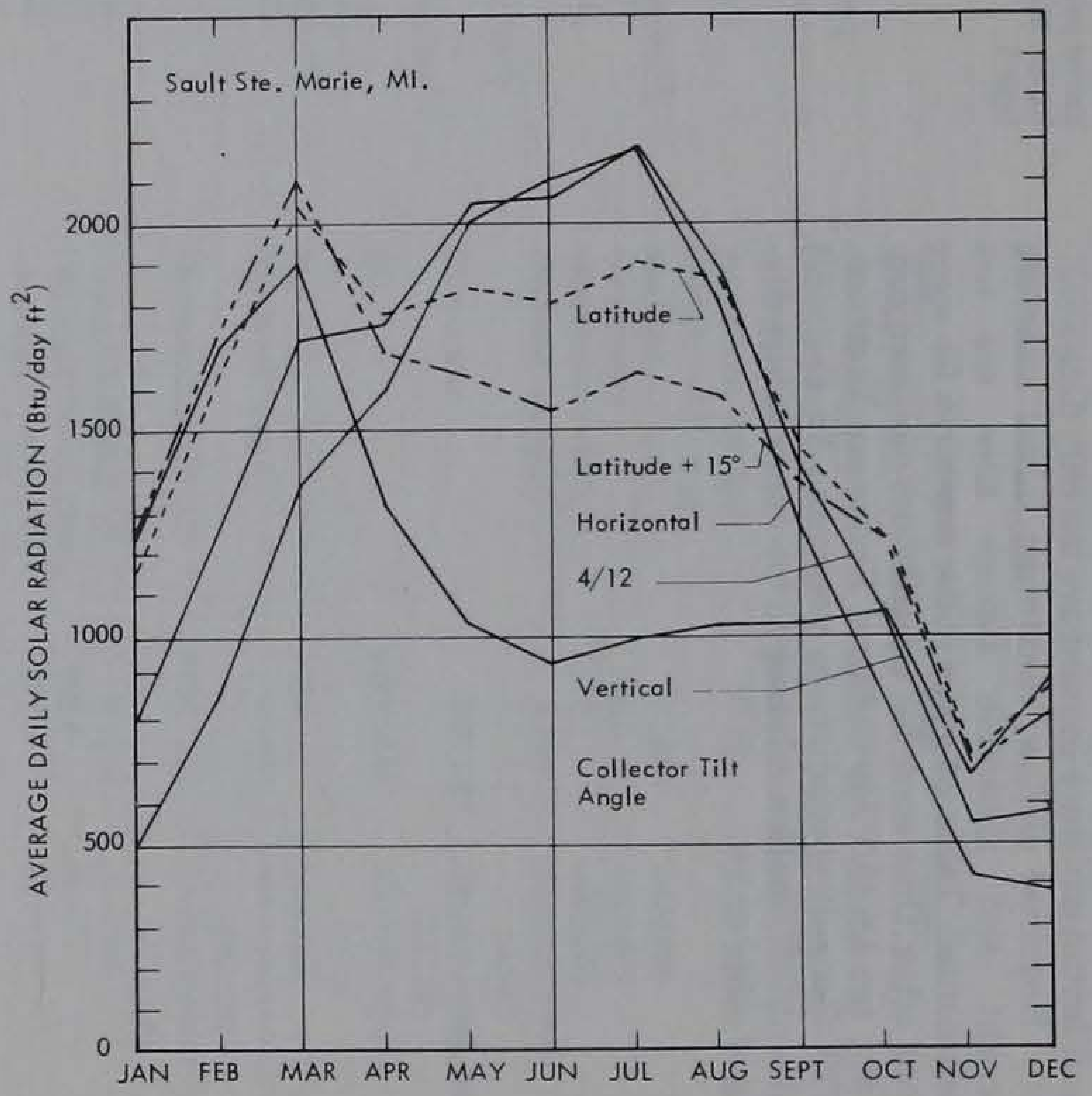
Table 23l. St. Cloud, MN (45.6°North Latitude)

Month	Horizontal (0°)	Collector tilt angle 4/12 (18°)	Latitude (46°)	Lat. + 15° (61°)	Vertical (90°)
	------Average total daily radiation, Btu/day-ft^2------				
January	633	1054	1526	1677	1699
February	977	1418	1880	2005	1944
March	1383	1733	2024	2049	1810
April	1598	1747	1735	1610	1158
May	1859	1891	1713	1507	950
June	2003	1968	1707	1465	876
July	2088	2064	1801	1549	923
August	1828	1896	1756	1561	1003
September	1369	1542	1576	1480	1084
October	890	1113	1277	1272	1065
November	545	769	986	1034	962
December	463	758	1086	1189	1198

Table 23m. Sault Ste Marie, MI (46.5°North Latitude)

Month	Horizontal (0°)	Collector tilt angle 4/12 (18°)	Latitude (47°)	Lat. + 15° (62°)	Vertical (90°)
	------Average total daily radiation, Btu/day-ft^2------				
January	489	790	1135	1240	1252
February	844	1213	1609	1711	1664
March	1337	1688	2005	2045	1858
April	1559	1716	1741	1644	1279
May	1962	2004	1813	1593	1016
June	2064	2033	1757	1506	914
July	2149	2131	1854	1592	963
August	1768	1837	1700	1511	991
September	1207	1352	1376	1289	958
October	809	1009	1160	1154	977
November	392	520	646	670	625
December	360	567	804	876	883





Low temperature drying of crops other than corn is not well developed. Static pressure information and equilibrium moisture content are the only data available. Required airflow, maximum initial moisture content, and allowable storage time are not documented. Table 24 gives static pressures for some crops other than corn; for equilibrium moisture contents, see D245.3 Agricultural Engineers Yearbook, 1979. Consult specialists in your area for the most current information relating to low temperature drying of other crops.

Table 24. Static pressure.

Data for wheat, barley, soybeans from "Grain Drying on the Farm," an extension publication from N. Dakota State University. Sunflower data from L. F. Backer, NDSU. Sorghum values estimated at 2.5 times corn values given in Table 5.

Grain Depth ft.	Airflow, cfm/bu		
	1	2	3
Wheat	- inches water -		
4	0.5	0.8	1.1
6	0.9	1.6	2.4
8	1.4	2.5	4.3
10	2.0	4.3	7.8
Barley			
4	0.4	0.6	0.8
6	0.6	1.0	1.5
8	0.9	1.5	2.7
10	1.3	2.2	4.3
Soybeans			
4	0.3	0.4	0.4
6	0.4	0.6	0.8
8	0.5	0.8	1.2
10	0.6	1.3	2.0
12	0.9	1.8	2.9
Sunflowers			
4	0.1	0.2	0.3
6	0.2	0.4	0.7
8	0.3	0.7	1.2
10	0.4	1.1	1.9
12	0.6	1.6	2.8
14	0.8	2.2	3.8
16	1.1	2.9	5.0
18	1.4	3.6	6.4
20	1.7	4.5	7.9
Sorghum			
4	0.3	0.5	1.0
6	0.5	1.3	2.5
8	1.3	2.5	5.3
10	2.0	4.3	9.0
12	3.0	6.5	14.3
14	4.3	9.3	21.0

SI (METRIC) CONVERSIONS

Multiply to the right: in. x 2.54 = cm
Divide to the left : cm/2.54 = inches

Unit	Times	Equals
Length		
inches	2.540	centimeters (cm)
feet	0.3048	meters (m)
yards	0.9144	meters (m)
miles	1.609	kilometers (km)
Area		
sq. inches	6.451	sq. centimeters (cm^2)
sq. feet	0.09290	sq. meters (m^2)
sq. yards	0.8361	sq. meters (m^2)
acres	0.4047	hectares (ha)
sq. miles	2.590	sq. kilometers (km^2)
Volume		
cu. inches	16.34	cu. centimeters (cm^3)
cu. inches	0.01634	liters (L)
cu. feet	0.02832	cu. meters (m^3)
teaspoons	4.928	milliliters (mL)
fl. ounces	29.57	milliliters (mL)
quarts (liquid)	0.9464	liters (L)
gallons (liquid)	4.546	liters (L)
Mass		
ounce (dry)	0.02835	kilograms (kg)
pounds	0.4536	kilograms (kg)
ton (2000 lb)	907.2	kilograms (kg)
ton (2000 lb)	0.9072	tonne (t)
Velocity		
feet/minute (fpm)	0.005080	meters/second (m/s)
miles/hour (mph)	1.609	kilometers/hour (km/h)
Flowrate		
cu. feet/minute (cfm)	0.0004719	cu. meters/second (m^3/s)
gallons/minute (gpm)	0.00006309	cu. meters/second (m^3/s)

Unit	Times	Equals
Stress/Pressure		
inches of water (60°F)	248.8	pascals (Pa)
inches of mercury (60°F)	3377.	pascals (Pa)
pounds/sq. inch (psi)	6895	pascals (pa)
pounds/sq. foot (psf)	47.88	pascals (Pa)
Heat/Power/Energy		
Btu/hour	0.2929	watts (W)
horsepower	746.0	watts (W)
kilocalorie/second	4184.	watts (W)
Btu/hour · sq. foot	3.154	watts/sq. meter (W/m^2)
Btu/sq. foot	0.01136	megajoule/sq. meter (MJ/m^2)
Btu	0.0003182	kilowatt-hour (kWh)
Btu	1054.	joule (J)
Btu·in/h·ft^2·deg F	0.1441	watts/meter·kelvin (W/m·K)
Btu/pound·deg F	4184.	joule/kilogram·kelvin (J/kg·K)
R (deg F·h·ft^2/Btu)	0.1761	(K·m^2/W)
Langley/minute (Ly/min)	696.8	W/m^2
Langley/minute (Ly/min)	221.2	Btu/h·ft^2

Temperature
Fahrenheit (F); Celcius (C); kelvin (K)
C = (F - 32) /1.8
F = (1.8 x C) + 32
K = C + 273.15 = 273.15 + (F - 32) / 1.8

Prefixes
To get larger or smaller units, use prefixes.

Prefix	**Symbol**	**Factor**
nano	n	10^{-9} = 0.000 000 001
micro	μ	10^{-6} = 0.000 001
milli	m	10^{-3} = 0.001
centi*	c	10^{-2} = 0.01
deci*	d	10^{-1} = 0.1
deka*	da	10
hecto*	h	100 = 10^2
kilo	k	1 000 = 10^3
mega	M	1 000 000 = 10^6
giga	G	1 000 000 000 = 10^9

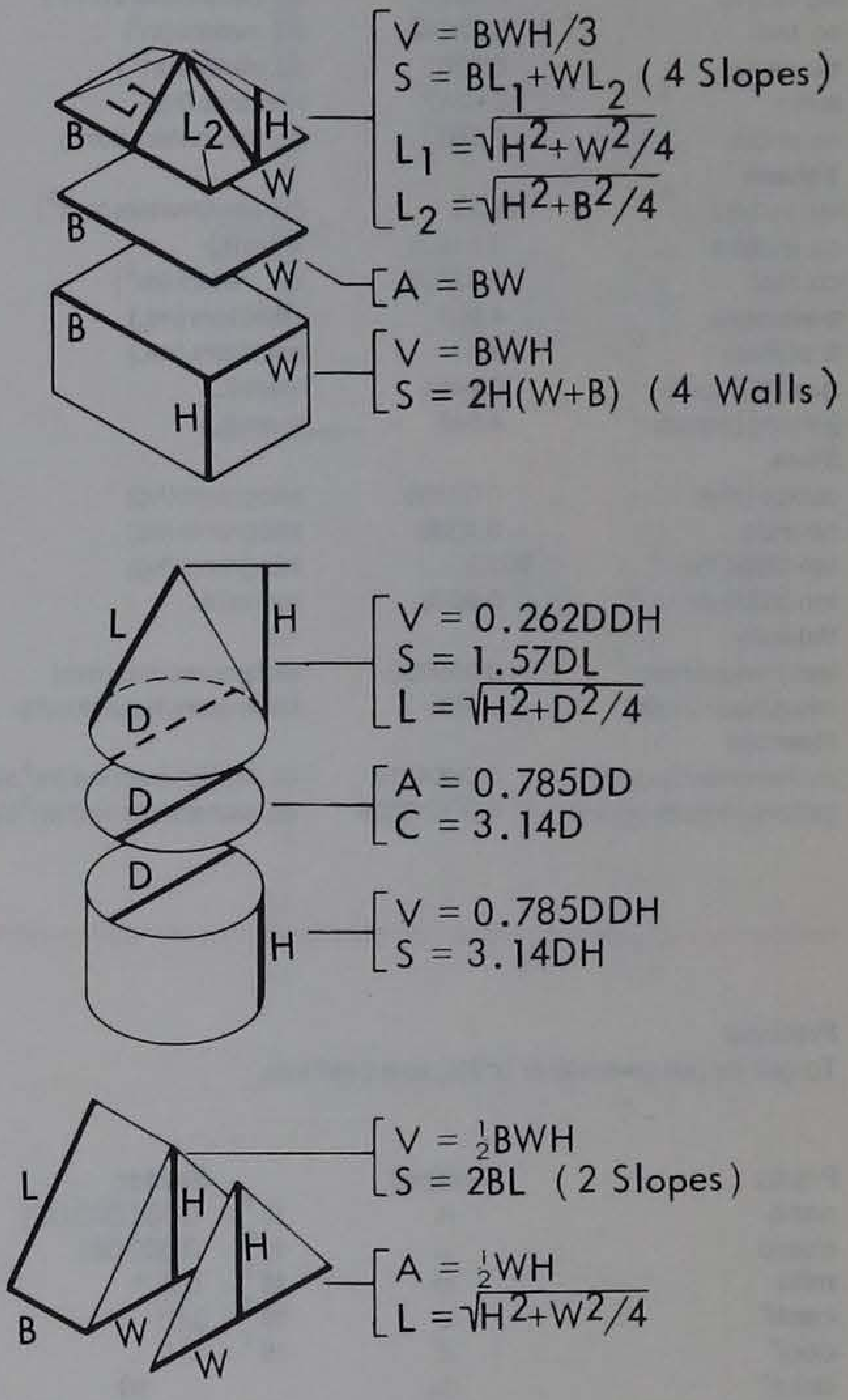
*Avoided in technical and scientific writing.
1 ft = 0.3048 m = 304.8 mm = 0.000 304 8 km

ABBREVIATIONS, SYMBOLS

(99 is arbitrary number)

AST	allowable storage time
Btu	British thermal unit
bu	bushel
cfm	cubic feet per minute
cu ft	cubic feet
F	degrees Fahrenheit
fpm	feet per minute
FRP	fiberglass reinforced plastic
ft^2	square feet
ft^3	cubic feet
gal	gallon
hr	hour
hp	horsepower
kW	kilowatt
kWh	kilowatt-hour
lb	pound
o.c.	on centers
PT	preservative treated
R	insulation resistance
sq ft	square feet
yr	year
%	percent
99°	degrees of angle
99'	feet
99"	inches
$	dollar
¢	cent

AREAS & VOLUMES



$V = BWH/3$
$S = BL_1 + WL_2$ (4 Slopes)
$L_1 = \sqrt{H^2 + W^2/4}$
$L_2 = \sqrt{H^2 + B^2/4}$

$A = BW$

$V = BWH$
$S = 2H(W+B)$ (4 Walls)

$V = 0.262DDH$
$S = 1.57DL$
$L = \sqrt{H^2 + D^2/4}$

$A = 0.785DD$
$C = 3.14D$

$V = 0.785DDH$
$S = 3.14DH$

$V = \frac{1}{2}BWH$
$S = 2BL$ (2 Slopes)

$A = \frac{1}{2}WH$
$L = \sqrt{H^2 + W^2/4}$

V = Volume
A = Area
S = Surface Area
L = Length of Slope
C = Circumference

GLOSSARY OF SOLAR TERMS

ABSORBER PLATE—Collector part that absorbs solar radiation, converts it to heat energy, and transfers the heat to the working fluid.

ABSORPTANCE—The fraction, between 0 and 1, of incident radiation that is absorbed by a material.

ACTIVE SYSTEM—A solar system requiring pumps or fans to move the working fluid.

ALTITUDE, SOLAR—The angle between the sun's rays and a horizontal surface.

AMBIENT TEMPERATURE—The outdoor or surrounding temperature.

ANGLE OF INCIDENCE—The angle between the sun's rays and a perpendicular line to the surface on which sunlight is falling.

AZIMUTH, SOLAR—The angle between a north-south line and the horizontal projection of the sun's rays.

BACKPLATE—Back of a solar collector; part farthest from sun.

BTU—British thermal unit; a unit of energy; the amount of energy required to warm one pound of water one degree Fahrenheit.

CFM—Cubic feet per minute (ft^3/min); unit of airflow.

COEFFICIENT OF THERMAL EXPANSION—The change in length of a material for each degree change in temperature.

COLLECTOR—device to receive and absorb solar energy and convert it to heat.

CONDENSATE—The liquid formed when a vapor condenses.

CONDUCTION—Heat transfer through or between bodies in physical contact—involves no fluid motion.

CONDUCTIVITY—Property indicating how readily heat moves through a material.

CONVECTION—Heat transfer by fluid motion.

COVER—Collector part that admits solar radiation to the absorber, shields it from heat losses to the wind, and reduces longwave radiation losses.

DESICCANT—A drying agent; can remove moisture from other substances.

DIFFERENTIAL THERMOSTAT—A switch that makes or breaks contact when the temperature difference between two points exceeds, or falls below, the setpoint.

DIFFUSE RADIATION—Sunlight scattered by particles in the atmosphere; solar energy available on a cloudy day.

DIRECT GAIN—Solar heating by direct exposure to sunlight.

DIRECT RADIATION—Sunlight arriving without diffusion or scattering; also called direct beam radiation.

EMITTANCE—The fraction, between 0 and 1, that indicates the tendency of a material to radiate or emit energy of a specified wavelength.

EQUINOX—Date when the Earth's axis of rotation has a 0° tilt angle toward the sun; day and night are equal length all over the earth; about March 21 and September 21.

FIBER BLOOM—The exposure of glass fibers at the surface of FRP due to the deterioration of the binding resin.

FIXED COLLECTOR—One that does not follow the sun.

FLUID—Any liquid or gas.

FOSSIL FUELS—Natural fuels formed from prehistoric plants and animals; e.g. coal, petroleum, natural gas.

FREESTANDING—Self-supporting; not mounted on or part of another structure.

FRP—Fiberglass reinforced plastic; materials with glass fibers imbedded in a polyester resin.

GLAUBERS SALT—Sodium sulfate decahydrate ($Na_2 SO_4 . 10H_2 O$) latent heat storage material; melting point = 91F and heat of fusion = 108 Btu/lb.

GLAZING—The transparent cover material on a solar collector.

HEADER—Manifold; a larger diameter pipe connecting the smaller tubes through the absorber of a solar collector.

HEAT EXCHANGER—A device to transfer heat from one fluid to another without direct fluid contact; usually metal tubes with one fluid inside and the other outside them.

HEAT OF FUSION—The latent heat required to melt a material or the heat released when it freezes; Btu/lb.

HEATING WATER—Water (or water plus antifreeze) that carries heat in liquid space or floor heating systems.

INCIDENT ANGLE—Angle of incidence.

INFRARED RADIATION—Radiation with wavelengths longer than 0.7 micrometers; energy radiated by objects at less than 1000F; also called longwave radiation.

INSOLATION—Sunlight or solar energy; includes ultraviolet, visible, and infrared radiation; Btu/hr-ft^2.

LATENT HEAT—The energy absorbed or released by a material when it changes phases (from solid to liquid, for example); no temperature change is involved.

LATITUDE—distance in degrees north or south of the equator on the earth's surface.

LONGWAVE RADIATION—Low energy radiation with wavelengths longer than 3 micrometers; the type of radiation emitted by solar collector absorber plates; thermal radiation.

LOW GRADE HEAT—The energy in materials at low temperatures, or only slightly warmer than their surroundings.

NATURAL CONVECTION—Natural heat transfer caused by the density difference between hot and cold fluids.

NORMAL—Perpendicular; a line at right angles (90°) to a surface.

OPAQUE—Not transparent; does not let light through.

OUTGASSING—The release of a gas or vapor from organic materials as they deteriorate.

PASSIVE SYSTEM—A solar system that relies on natural movement of the working fluid, or heating by direct exposure to sunlight; no extra pumps or fans.

PHASE CHANGE MATERIAL—A material that stores energy as latent heat.

POTABLE—Fit for drinking.

REFLECTANCE—The fraction, between 0 and 1, of incident radiation that reflects off the surface of a material.

RETROFIT—Adaptation of a technical innovation, such as a solar collector, to an existing building.

R VALUE—The resistance of a material to heat flow; good insulators have high R values.

SELECTIVE SURFACE—One for which longwave emittance is considerbly less than shortwave absorptance; a high fraction of incoming solar energy is absorbed, but little heat energy is lost by longwave radiation.

SENSIBLE HEAT—The energy applied to raise the temperature of a material or the energy removed to cool it.

SERPENTINE—Snake-like; having a curving, winding shape.

SERVICE HOT WATER—Hot water for washing, cleaning, or cooking; must be potable.

SHORTWAVE RADIATION—High energy radiation with wavelengths shorter than 3 micrometers; radiation emitted by very hot objects.

SIDEPLATE—Side of a solar collector; holds absorber and cover in place.

SOLAR CONSTANT—The average amount of solar energy available on a sun-following surface just outside the Earth's atmosphere; the accepted value is 428 Btu/hr-ft^2.

SOLAR TIME—Time based on the position of the sun; the sun is at its highest point in the sky (zenith) for the day at solar noon.

SPECIFIC HEAT—The amount of heat required to raise the temperature of a unit mass of material one degree.

STAGNANT—Not running or flowing.

STAGNATION—No fluid movement through a solar collector; temperatures to 300F can develop when the sun is shining.

SUMMER SOLSTICE—Longest day of the year in the northern hemisphere; the first day of summer; about June 21; the earth has a maximum tilt toward the sun.

SUN-FOLLOWING—Tracks or follows the sun; the solar angle of incidence is always 0°.

THERMAL BREAK—An insulating material placed between two heat conductors to reduce conduction heat transfer.

TILT ANGLE—The angle between a collector surface and a horizontal surface.

TRACKING—Able to follow the movement of the sun.

TRANSMITTANCE—The fraction, between 0 and 1, of incident radiation that can pass through a material.

TROMBE WALL—A massive concrete, brick or adobe wall on the south side of passively heated solar structures; solar energy heats the wall during the day and heat is released to the structure at night.

ULTRAVIOLET LIGHT—Radiation with wavelengths shorter than 0.4 micrometers; one high energy component of sunlight; breaks down some rubber and plastic materials.

WINTER SOLSTICE—Shortest day of the year in the northern hemisphere; first day of winter; about December 21; time when the northern hemisphere has the maximum tilt away from the sun.

WORKING FLUID—Air or liquid that removes heat from the solar collector absorber.

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