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In Minnesota, contact Larry Jacobson, extension agricultural engineer

Earth Tempering of Ventilation Air

Authors:
Warren D. Goetsch, University of Illinois
Larry Jacobson, University of Minnesota
Randall Reeder, Ohio State University
Dennis Stombaugh, Ohio State University

Reviewers:
Eldridge Collins, Jr., Virginia Polytechnic Institute and State University
Dexter Johnson, North Dakota State University
Richard Phillips, Pennsylvania State University
Harold and Dean Rogers, Petersburg, Illinois
David Shelton, University of Nebraska

Earth tempering of ventilation air for swine buildings is being considered by many producers because of the moderate fluctuations in soil temperatures at shallow depths. Depending on the season, incoming ventilation air is heated or cooled as it passes through a buried tube. The soil serves as a heat sink in the summer and as a heat source in the winter, thus giving almost year-round temperature modification. It has the potential to significantly reduce heating costs during winter and provide zone cooling during summer.

Soil Temperature

Soil temperature is one of the most important factors affecting design and performance of earth-tube heat exchanger systems. Soil temperatures vary with soil type, depth, moisture content, time of year, and geographic location.

The mean annual ground temperatures for various locations in the United States are given in Figure 1.* In the central U.S., these mean annual ground temperatures range from 49°F. in St. Paul, Minnesota, to 58°F. in Lexington, Kentucky, and from 52°F. in Ames, Iowa to 55°F. in Columbus, Ohio. The variation of ground temperature from this yearly mean at any site is suggested by Figure 2. The amount of temperature variation decreases as depth increases. For example, at a depth of 6 ft., the yearly variation of a typical clay soil can be expected to range from 11 degrees above to 11 below the mean annual ground temperature, or a total yearly variation of approximately 22 degrees. At a depth of 10 ft., this variation is reduced to plus or minus 6 degrees F. or a total variation of 12 degrees.

The time of year when the ground temperature is at the extreme is also important in the design and performance of a system. Soil temperature fluctuations lag behind surface temperature changes due to the heat storage capacity of the soil. The soil surface reaches maximum temperature during the heat of the summer, but soil 10-12 ft. deep may not reach its peak temperature until almost three months later. This thermal lag at the 10 ft. depth (Fig. 3) helps both the heating and cooling performance of these systems. During the winter, soil temperatures at this depth are at the fall season level, making the soil near the mean annual ground temperature, thus adding to the heating capabilities of a system. The reverse is true during the summer months, when the soil temperatures at the 10-12 ft. depth are springlike and can cool the ventilation air.

Soil types and moisture content also affect the ground temperature variation. Soils with increasing sand content tend to have larger temperature variations at deeper depths than clay soils. Soil moisture and ground water elevation also affect soil temperature. Seasonal temperature variation is larger in very moist soils as compared to very dry ones due to the increase in heat transfer through soils whose voids are filled with water.

System Design

The typical earth-tube tempering or heat exchanger system consists of a heat exchanger field, a collection

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* The drawings in Figures 1, 2, and 3 first appeared in "Underground Building Climate" by Kenneth Labs, in the October 1979 issue of *Solar Age*, c 1979 SolarVision, Inc., Harrisville, NH 03450. All rights reserved. Reprinted and published by permission.

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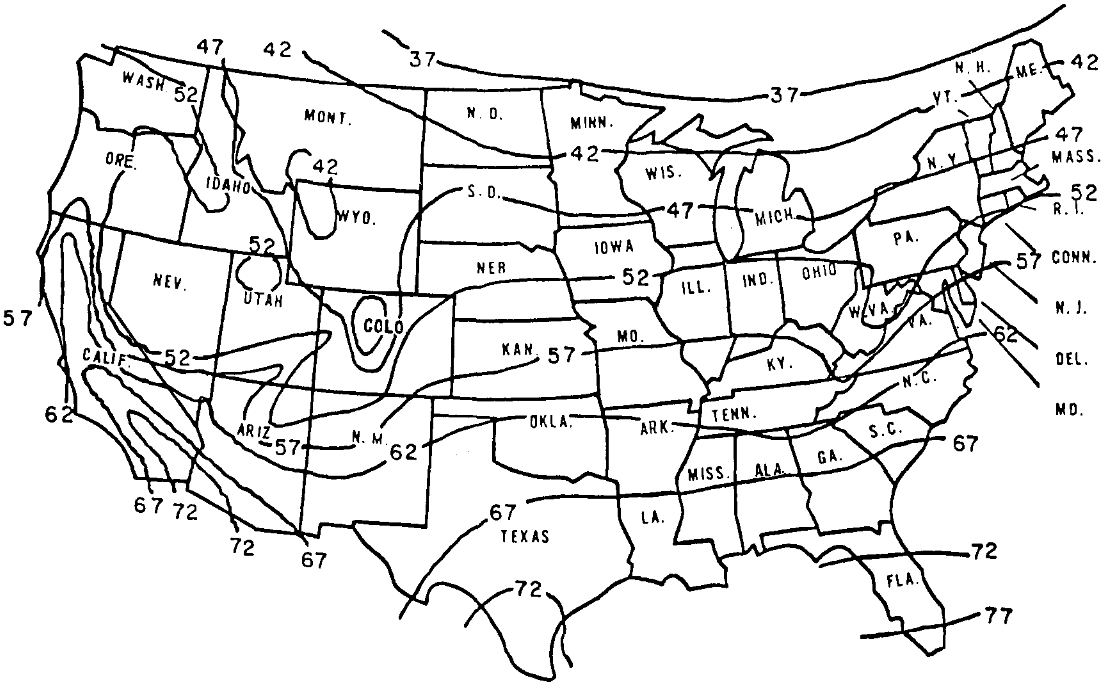

Figure 1. Well-water isotherms indicating the mean annual ground temperatures for the 48 contiguous states.

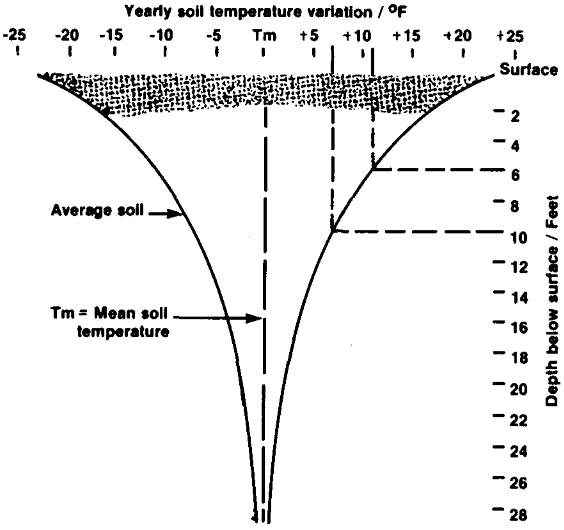

Figure 2. Yearly variation of soil temperature with relation to depth below surface for average soil.

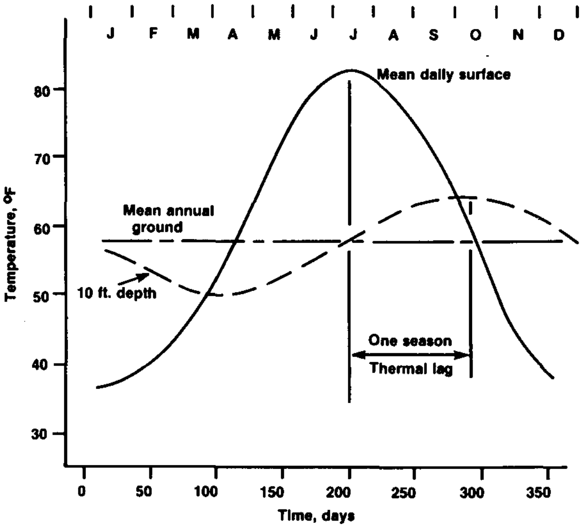

Figure 3. Annual ground temperature curves at the soil surface, at a depth of 10 ft., and the annual mean for generalized conditions at Lexington, Kentucky, showing the degree of thermal lag at the 10-ft. depth.

Table 1. Recommended ventilation rates for swine in environmentally regulated buildings.

			Hot weather			
			Zone cooling			
Swine type	Cold weather	Mild weather	Uncooled air	Evaporative cooled air	Air-conditioned air	Normal
	cfm per head					
Sow and litter	20	80	70	50	30	500
Prenursery (12-30 lb)	2	10	-	-	-	25
Nursery (30-75 lb)	3	15	-	-	-	35
Growing (75-150 lb)	7	24	-	-	-	75
Finishing (150-220 lb)	10	35	-	-	-	120
Gestation sow (325 lb)	12	40	45	30	20	150*
Boar (400 lb)	14	50	60	40	20	180

* 300 cfm for gestating sows or boars in a breeding facility due to low animal density.

duct/fan house, and a building air distribution system. Each of these portions must be adequately sized to insure proper performance. The following sections may help to explain the many tradeoffs in system design.

Airflow Capacity. In general, much more air is required for summer ventilation than for winter. If zone cooling is used, the difference between the two rates is much less (Table 1). For example, the recommended summer zone cooling rate for a sow and litter is 70 cu. ft. per minute (cfm) of uncooled air per farrowing crate, 50 cfm for evaporative cooled air, and 30 cfm for air-conditioned air. Air tempered by an earth-tube system should be somewhat cooler and dryer than evaporative cooled air (depending on climate), but for planning purposes use the 50 cfm per crate. During winter, the recommended cold weather ventilation rate is 20 cfm per crate. With the system designed for a capacity of 50 cfm per crate, there is an additional 30 cfm which can be used for mild weather room tempering as needed or it can be used to preheat the winter air of a compatible nearby nursery. Similar design capacity figures are shown for gestation sows, boars, and growing and finishing pigs in Table 1.

Table 2. Ventilation comparison between a farrowing house with and without an earth-tube heat exchanger system.

	Ventilation rate requirement	
Ventilation rate type*	Normal building without earth system*	Building with earth system
Cold weather	20 cfm/crate (outside air)	20 cfm/crate (earth-tempered outside air)
Mild weather	80 cfm/crate (outside air)	50 cfm/crate (earth-tempered outside air)
Hot weather	500 cfm/crate (outside air)	250 cfm/crate (50 cfm/crate earth-tempered plus 200 cfm/ crate outside air)

* Same as Table 1.

Comparison of the air volume requirements for a farrowing house with and without the use of an earth-tube heat exchanger system is shown in Table 2. A properly designed and managed system allows the producer to reduce whole building ventilation rate by one-half during the summer (50 cfm/crate of earth zone cooled air plus 200 cfm/crate outside air versus the normal 500 cfm/crate outside air recommendation). If zone cooling is not desired or possible because of interior room design, whole-room cooling may be an option. For whole-room-cooling planning purposes use an air volume of 100 cfm per farrowing crate or twice the normal zone cooling rate. Adequate building insulation levels and proper room air distribution systems are extremely important to ensure successful ventilation with this type of system (See PIH-65, *Insulation for Swine Housing,* and PIH 87, *Cooling Swine*). Zone cooling is recommended over whole-room cooling because it is more cost effective, especially in the farrowing and gestation units.

Heat Exchanger Field Design. Both soil characteristics and tubing factors affect the design and performance of a system. Soil characteristics include soil type, moisture content, and water table elevation. Temperature levels for various soil types indicate the less favorable performance of sandy soils; so avoid these if possible. If sandy soils must be used, the number of lines, line lengths, and/or depth should be increased by 10 to 20% to offset this effect. Moisture content increases the heat-transfer capability of the system. Therefore, a system installed in an area with a shallow water table should have the lines buried below the average yearly elevation of the water table for maximum performance. Such a system must be well sealed to minimize ground water seepage and additional pumping costs. Construction should take place during periods of low water table to reduce the use of pumps and possibly unstable trench sides and bottom.

Air-tubing factors include diameter, length, depth of placement, and shape of the tube. Typically, *nonperforated* corrugated plastic drainage tubing is used

Table 3. Earth-tube heat exchanger line dimensions and capacities.

Tube diameter (in.)	Nominal tube area (sq. in.)	Relative cost per ft.*	Suggested line lengths (ft.)†	Suggested airflow per tube (cfm)‡
4	12.6	$0.25	65 -- 85	50
5	19.6	0.35	80 -- 105	80
6	28.3	0.55	100 -- 130	110
8	50.3	0.90	130 -- 170	200
10	78.5	1.85	160 -- 210	300
12	113.1	2.30	200 -- 250	450
15	176.7	3.80	250 -- 320	700
18	254.5	6.30	300 -- 380	1000
24	452.4	14.40	400 -- 500	1800

* Costs vary with different manufacturers and change over time. These costs are only offered to give a relative figure for different sizes of tube.

† Line length ranges indicate the effect of soil type and moisture content on line dimensions. The low end of the range corresponds to a wet clay soil type and is based on 1.3 sq. ft. of tube surface area per cfm of airflow. The high end of the range corresponds to a dry sand soil condition and is based on 2.0 sq. ft. of tube surface area per cfm of airflow. All surface area calculations were made assuming smooth pipe for simplicity.

‡ These airflow rates allow for a air velocity of 500 to 600 fpm.

because of its availability and cost. The recommended airflow rates for various tubing diameters are shown in Table 3. These airflows are based on an air velocity in the tube of 500-600 ft. per minute (fpm). Divide the total airflow needed for the system by the recommended flow rate per tube to indicate the number of tubes needed for a given system. Table 3 also shows the recommended tubing length for various diameters of tubing. This length is based on an air contact (heat-exchange surface) of 1.3-2.0 sq. ft. of tube surface per cfm of airflow (figures are based on smooth pipe for simplicity of calculation). Small diameter tubing, such as the 3-, 4-, or 5-in. sizes, are impractical because of the large number of lines needed to provide enough air capacity for a typical system; thus the 8-, 10-, and 12-in. diameters are the most practical.

Layout. Several system layouts are possible, including the wagon wheel (radial) or the lateral (see Figs. 4 and 5). Material and trenching costs are normally less for the wagon wheel pattern because no manifold lines are used; however, excavation can be difficult near the collection duct. Manifold lines must be much larger than lateral lines, and tubing materials and trenching are more expensive. However, a lateral system with a manifold may be the only option when surrounding buildings, roads, or fields limit the area available for installing the system. The spacing between lateral lines need not be uniform, but each lateral should be of equal length to keep the airflow equal. Laterals do not need to run straight, but abrupt turns should be avoided.

Placement. The tubing should be buried to a depth of 7-12 ft. depending on installation costs and geographic location. System thermal performance will be better with maximum depth. If installation costs are prohibitive, somewhat shallower depths may provide a more beneficial economic return.

Space lines at least 8-10 ft. apart to maximize soil heat storage and minimize the chance of tubing deflection and damage during construction. Trenches with multiple tubes and closer tube spacings may be used to reduce construction costs; however, line length should be increased to maintain adequate soil mass for heat transfer. For example, four 6-in. diameter tubes have about the same airflow capacity as one 12-in. diameter tube. If four 6-in. lines are installed in a single trench, their length should be the same as the 12-in. recommendation of 200-250 ft. instead of the normal 6-in. tube recommendation of 100-130 ft. Slope lines at a minimum of 2-3 in. per 100 ft. to a U-trap and gravity drainage line at the outer tube ends or to a drain sump at the collection duct. *Constant slope is critical* because any low spots in the lines could fill with water and restrict air flow.

Tubing should be installed carefully, in accordance with ASTM Standard Designation: F 449-76.† Either trenchers or backhoes can be used for excavation, but hand blinding (careful placement of select material over and on the sides of the tubing) and narrow trenches with rounded bottoms should be used to ensure constant slope and minimal tube deflection and damage. Modern trenchers are equipped with laser plane-grade guides that ensure a constant slope. However, most trenchers are restricted to depths of less than 7 ft. unless a special adapter is available, and 2-3 ft. of topsoil may need to be removed before trenching if trenchers are to be used (Fig. 6). Backhoes are more expensive but are available for depths down to 12 ft. and can, with care, maintain a constant slope (Fig. 7). They can be used when trenchers are not practical; however, due to the extreme depths and possible cave-in problems, trench sides should be sloped and bulkheads may be needed to ensure a safe working area. Minimum trench width should be 6 in. wider than the outside diameter of the tubing. If extremely wide trenches are used, the tubing should be placed in the corner of the trench against a trench wall.

At the outer end of the system, the tubes should curve up and extend 3 to 4 ft. above the soil surface to

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† Copies of the standard can be obtained by writing to: American Society for Testing and Materials, 1916 Race St., Philadelphia, PA 19013. Be sure to state "ASTM Standard Designation: F 449-76."

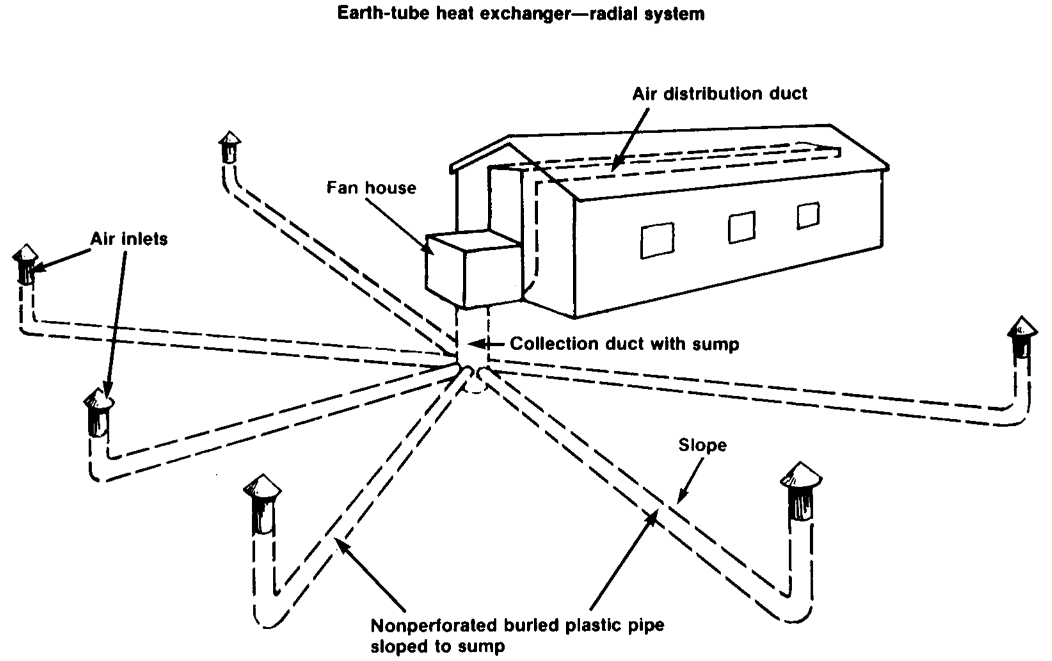

Figure 4. System layout using the wagon wheel or radial pattern.

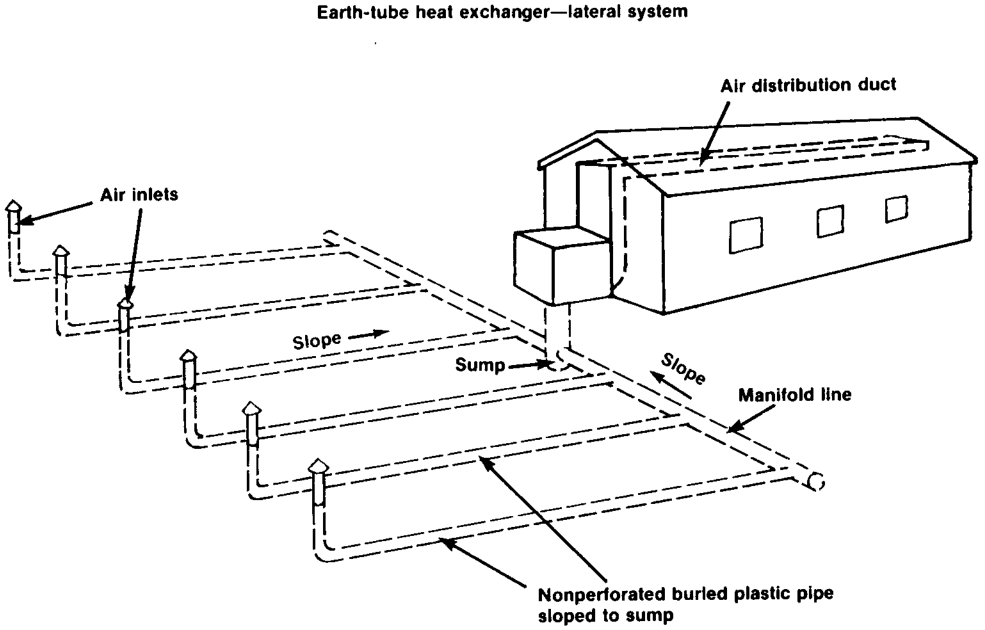

Figure 5. System layout using the lateral tubing pattern.

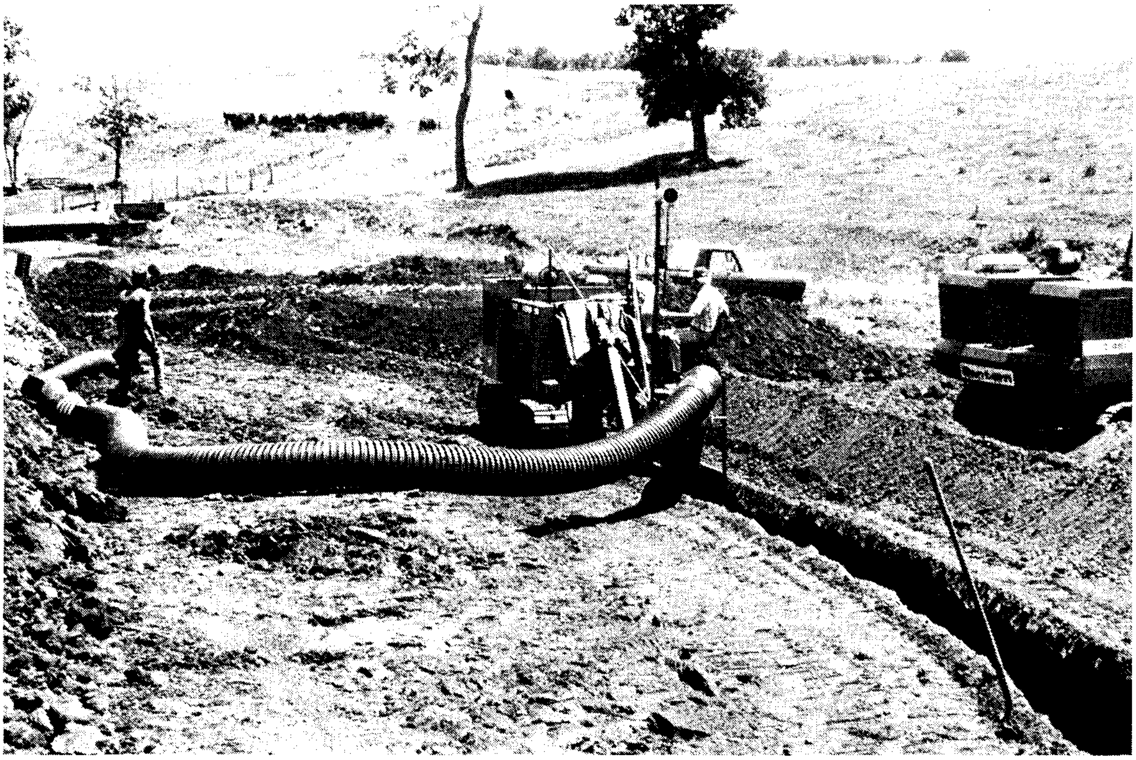

Figure 6. Chain-trencher excavating and installing 12-in. diameter tubing for a 1,600-cfm capacity system in Menard County, Illinois. Three to 4 ft. of soil was removed, using a bulldozer before the trencher was used to install the tubing an additional 6 ft. into the soil.

Figure 7. Backhoe excavating and installing 12-in. diameter tubing to a depth of 12 ft. for a 2,000-cfm capacity system in Sangamon County, Illinois. For safety reasons, the trench walls run up vertically only 6 ft. and the upper 6 ft. is set back to reduce cave-in problems. The evaporative cooler on the building roof is being replaced by the earth-tube heat exchanger system.

form the air inlet. Either rigid PVC pipe or corrugated plastic tubing can be used for the inlet risers; however, the tops should be screened to keep out debris and rodents and should be very visible to prevent damage from nearby machine traffic.

Collection Duct/Fan House Design. Common materials for collection ducts below grade include reinforced concrete, concrete blocks, and round steel. An example of one such reinforced concrete collection duct is shown in Figure 8. Size is determined by system airflow and wall area requirements to make the tubing connections. In general, collection ducts should provide enough wall area to connect the lines and enough cross-sectional area to keep airflow velocities below 500 fpm. Above grade, insulated wood construction is acceptable to enclose the airstream. A properly sized fan must be installed at the connection between the underground system (collection duct) and the building air distribution ducts. Determine the size of the above-grade duct by the size of fan to be enclosed and the type of service access entrance to be used. Normally,

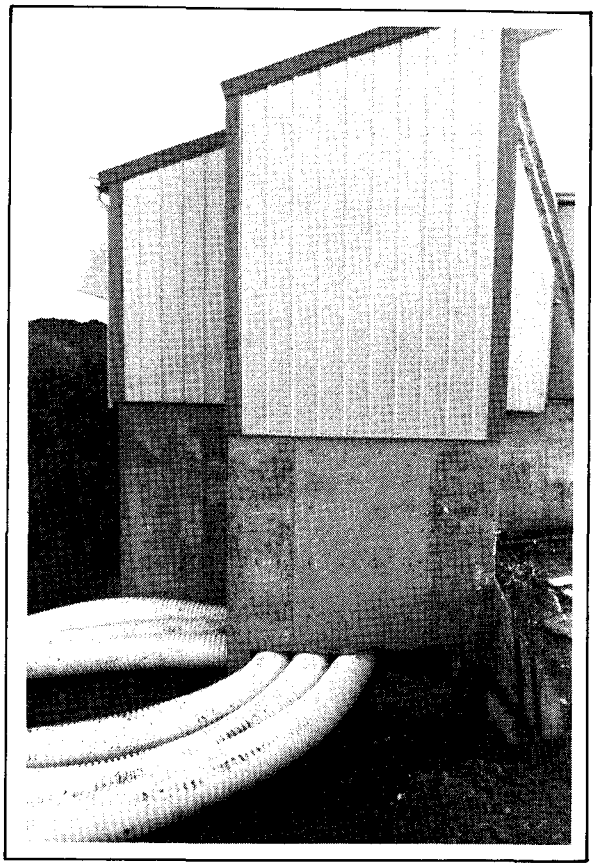

Figure 8. Reinforced concrete collection sump on a 4,000-cfm capacity system in Peoria County, Illinois. At the sump, the tubing lines are approximately 8 ft. below grade but slope away from the building where they become 10-12 ft. deep. A portion of the sump was chipped out after the producer decided to increase the number of lines in the system.

the above-ground portion can be constructed to the same dimensions as the below-grade portion and still provide enough area for fan installation, access, and maintenance.

Insulate the entire collection duct/fan house to at least R-19 to a depth of 6 ft. below grade with moisture-proof insulation. A closed cell polystyrene or polyurethane insulation is recommended. A reverse tempering effect has been noted on installations in Illinois where no insulation was used below the 3 ft. depth. In one case, air that had been cooled in the tubes was reheated 5 degrees as it passed through the duct/fan house into the building.

A fan should be located between the underground tubing system and the building air distribution system. Size this fan to deliver the desired airflows against **⅜ to ½-in. static pressure.** Usually, a two-speed fan would be best, with the maximum volume matched to the summer zone cooling rate and the smaller volume matched to the winter continuous ventilation rate. Tightly seal the collection duct and all connections to prevent short circuiting of air from outside directly into the duct, thus bypassing the tubing system.

Building Air Distribution System. The distribution system for the earth-tempered air consists of a fan, main duct or ducts, and downspouts (or drop ducts) located as needed for each animal (Figs. 9 and 10). In a farrowing house, locate a downspout above each individual crate with the airstream directed at the sow's head. The downspout should be located as close to the animal's head as possible to make full use of the cooled air. If spouts are within the animals' reach, they should be made pig-proof. Include dampers in the downspouts to close individual lines when crates are empty and to adjust airflow if needed.

Main duct and downspout dimensions are given in Table 4. These are minimum duct dimensions and should be increased if duct framing is located inside the airstream. Insulate ducts to at least R-6 to prevent heat gain and condensation during summer operation.

For winter operation, earth-tempered air can be routed through an existing room air distribution system, through room make-up air heaters, or the summer downspouts can be removed and tempered air can be introduced into rooms via the distribution duct openings along the room ceiling.

Design Example

Design an earth-tube heat exchanger for a 24-sow farrowing house. The summer zone-cooling ventilation rate equals 50 cfm per sow and litter, and the continuous winter rate is 20 cfm per sow and litter (Table 1). Therefore, the maximum airflow for the system (zone cooling) equals 1,200 cfm (50 cfm per sow x 24 sows), and minimum airflow equals 480 cfm (20 cfm per sow x 24 sows). During the winter, the extra 720 cfm capacity of the system could be used to heat and ventilate an adjoining nursery.

From Table 3, find that 6-in. tubing can carry 110 cfm per tube. Eleven 6-in. tubes are required (1,200 cfm divided by 110 cfm per tube). For 8-in. lines, use six tubes (1,200 cfm divided by 200 cfm per tube). For 10-in. tubing use four tubes (1,200 cfm divided by 300 cfm per tube). The suggested length for each tubing size is given in Table 3. A system using eleven 6-in. tubes, each 100-130 ft. long (depending on soil type); six 8-in. tubes, each 130-170 ft. long; or four 10-in. tubes, each 160-210 ft. long, would be satisfactory. Check the cost of trenching and materials in the area to determine which system would be most economical. The relative costs of different tubing sizes are also shown in Table 3. As the size of the tubing increases, the cost of the material goes up. The material cost increases are especially large if tubing of 10-in. diameter or more is used.

Manifold lines, when used, must carry the entire flow that goes through them at an appropriate velocity (refer to Table 3 for size). If six lateral lines of 8-in. tubing are installed, as arranged in Figure 5, the manifold running in each direction to the first lines needs to be 15 in. in diameter (200 cfm per 8-in. line x 3 lines = 600 cfm). The manifold can then be decreased to a 12-in. size to the second lines (200 cfm per 8-in. line x 2 lines = 400 cfm). After the second line is connected, the manifold can be reduced to an 8-in. diameter tube out to the last line. The vertical tube coming out of the ground should be a 24-in. tube or larger.

Size the fan to supply 1,200 cfm at the high setting and 480 cfm at the low setting while working against ⅜ to ½ in. of static pressure.

From Table 4, an 18- by 18-in. or 10- by 30-in. (inside dimensions) main duct will carry the 1,200 cfm airflow. If crate layout is such that two ducts are needed, two 12- by 12-in. or two 6- by 24-in. ducts could also be used. Also from Table 4, a 4-in. diameter downspout

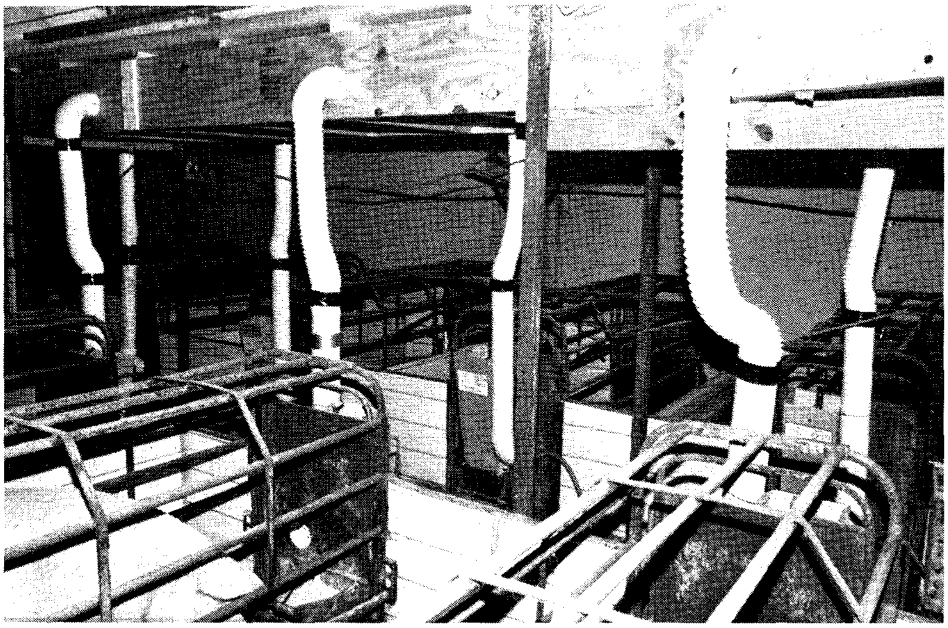

Figure 9. Tempered air to this 24-crate farrowing facility in Shelby County, Illinois, is carried down the center of the building via the insulated main duct shown. Downspouts are 4-in. diameter PVC pipe with flexible dryer hose used to allow opening and closing of crate doors.

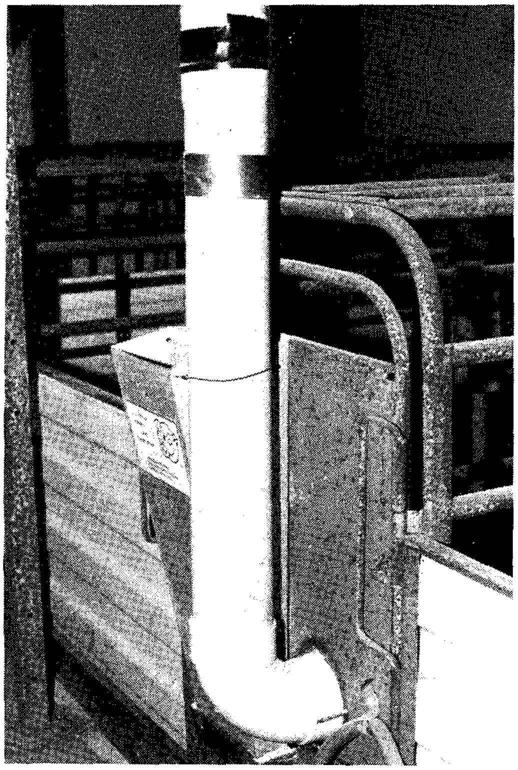

Figure 10. Downspouts can be used to bring the tempered air down into the crate a few inches away from the sow. Here PVC tubing has been used to direct the air through the crate door directly on the animal's snout.

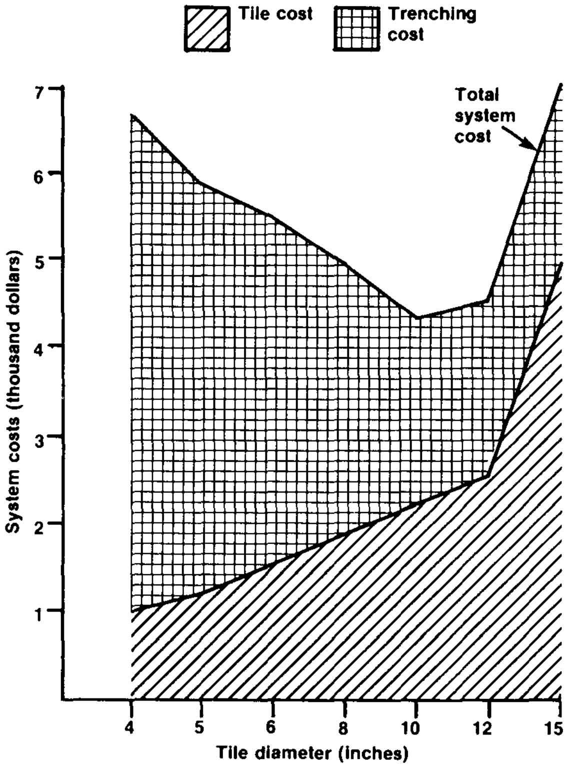

Figure 11. Tubing and trenching costs for a typical 2,000-cfm capacity system.

or a 3- by 3-in. square downspout would carry the desired 50 cfm per crate airflow to each animal.

System Costs

Major costs encountered when installing an earth-tube heat exchanger system include: excavation, tubing, fan, and the interior distribution system. Cost will vary with the depth of installation, excavation method, layout, and site constraints. Obtain cost estimates for the specific site, layout, and desired depth before selecting a final design. Figure 11 shows a typical breakdown between trenching and tubing costs for tubing of different diameters in a system delivering 2,000 cfm of air installed at an average depth of 9 ft. For a 2,000 cfm system, the 8-, 10-, and 12-in. tubing sizes were the most economical in this case. The figure also indicates average tubing and excavating costs are approximately $2 per cfm of air capacity. Fan and distribution system costs usually average approximately 50 cents to $1 per cfm of air capacity. Thus, total costs for an average system should range from $2.50 to $3 per cfm of system air capacity (1985 costs).

Performance Data

Several functioning systems have been monitored in Illinois during the past few years, including systems designed according to the guidelines presented here.

Table 4. Building air distribution main duct and downspout dimensions. Main duct sizes are based on duct air velocity of 600 fpm. Downspout sizes are based on air velocities of 800-1,000 fpm.*

		Inside duct dimensions if:	
	Air flow rate within duct	**Rectangular**	**Round**
	cu. ft./min.	**in. x in.**	**in. diam.**
Main duct sizes	250	6 x 10	9
	500	10 x 12	12
	750	10 x 18	15
	1000	12 x 20	18
	1250	15 x 20	
	1500	18 x 20	
	2000	18 x 27	
	2500	18 x 34	
	3000	18 x 40	
	3500	24 x 35	
	4000	24 x 40	
	5000	24 x 50	
	6000	30 x 48	
	7000	36 x 48	
	8000	36 x 54	
Downspout sizes	20	2 x 2	2½
	30	2 x 3	2½
	40	2½ x 3	3
	50	3 x 3	3½
	75	3 x 4½	4
	100	4 x 4½	5
	125	4 x 5½	
	150	4 x 6½	6
	175	4 x 8	
	200	6 x 6	
	250	6 x 7½	8

* It is the minimum cross-section area, not the actual duct dimensions given in the table, that is important. Almost any duct shape of comparable size should deliver the same amount of air.

Summer and winter performance curves for a 30-crate farrowing facility located near Springfield, Illinois, are shown in Figures 12 and 13. The system consists of five 12-in. lines, each 260 ft. long, buried about 10 ft. deep.

The outside temperature for a three-day period in August 1981 (Fig. 12) varied from 60 to 92°F. The earth-tempered air temperatures ranged from 64 to 69°F. The average sensible cooling effect during the three-day period was equivalent to 20,773 Btu/hr. The temperature of the outside air during the three-day period in January 1982 (Fig. 13) varied from +20 to -19°F., whereas the earth-tube output temperature was steady at 46 to 48°F., a maximum temperature increase of 67 degrees. The earth-tube heat exchanger provided about 40% of the heating required during the winter of 1981-82 by delivering tempered air at the approximate rate of 920 cfm.

Economic Payback

As with other alternative energy systems (solar and heat exchangers), tempering of ventilation air by earth-tubes is not free. Since the costs and returns vary considerably for earth-tube systems, a rigorous economic analysis would be both difficult and lengthy. However, to give some indication of economic payback for a system, the following example is provided, using the performance data and costs given above, plus estimated returns and expenses.

Figure 13 gives the "heating" performance of a system over three days in January from a 30-crate farrowing barn in Illinois. A relatively constant exhaust air temperature from the earth-tubes of 48°F. was recorded over this period. If one assumes this same temperature over the entire heating season (will probably be greater in the fall and less toward spring), then the amount of energy recovered per heating month can be found using the following relationship:

$Q = 1.1 \times 920 \text{ cfm} \times (T_o - T) \times 24 \times$ (number of days in month)

where

Q = Btu/month

T_o = temperature exiting tubing (48°F. for our example)

T = average monthly outside temperature

Using average monthly temperatures for central Illinois during the heating season (November through March), a total of 61.5 million Btu's of energy would be recovered. If this total is divided by 75,000 Btu's (amount of usable energy per gallon of L.P. gas) then this is the energy contained in 820 gal. of propane. At 75 cents per gallon, a total of $615 would be saved per year. Since a larger fan (½ h.p.) is needed in this system than with conventional ventilation, a total of $100 (2,000 kwh x 5 cents/kwh) should be subtracted from $615 for a net return of approximately $500 per year from heating.

Estimating the cooling benefits during the summer is much more difficult than calculating heat savings. It would be unfair not to consider the returns from cooling, especially when comparing the earth-tube system with solar units and air-to-air heat exchangers. Some animal scientists have estimated that 1 extra pig per litter occurs if a summer cooling system is used, because of reduced sow heat stress, more efficient sow milk pro-

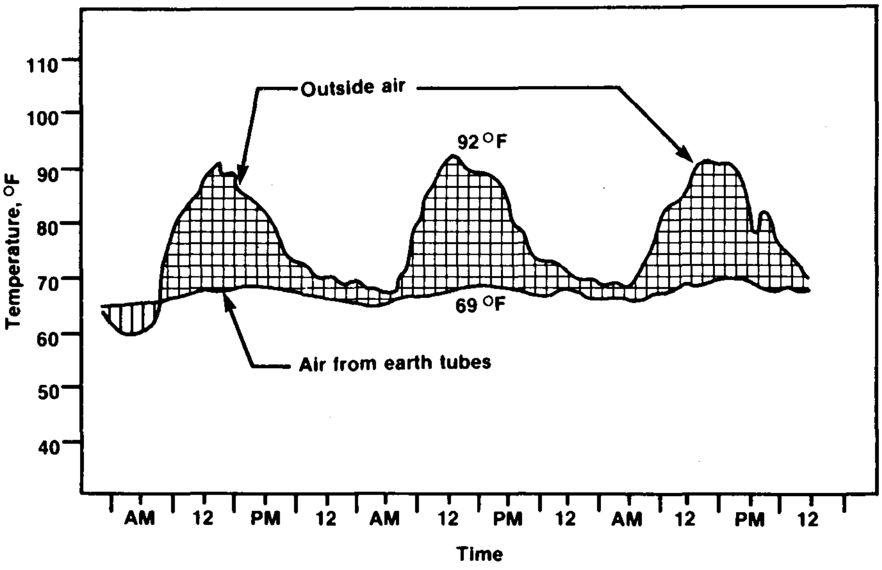

Figure 12. Performance of an earth-tube heat exchanger system during summer operation when delivering 2,000 cu. ft. of air per minute to a 30-crate farrowing house, August 23 to 25, 1981, Sangamon County, Illinois.

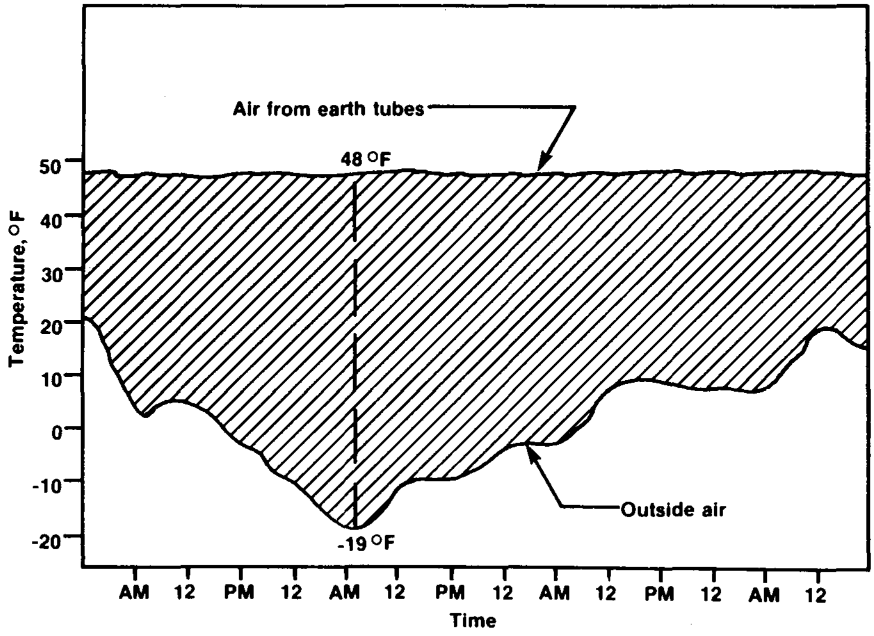

Figure 13. Performance of an earth-tube heat exchanger system during winter operation when delivering 920 cu. ft. of air per minute to a 30-crate farrowing house, January 9 to 12, 1982, Sangamon County, Illinois.

duction, and faster breeding. If that assumption is used in our example, then 30 extra pigs per farrowing would result for a total of 60 extra pigs (assume 2 farrowings per summer). If an estimated value of $15/extra pig is assumed, this results in a return of $900 due to cooling. Adding this amount to the annual estimated heat savings ($500), a total return of $1,400 per year results.

The costs of the above 1,500 cfm earth-tube system is estimated at $4,500, when using the $3/cfm figure discussed earlier (1,500 cfm x $3/cfm). The simple payback period, which excludes fuel price increases and interest, would be between three and four years. Consideration of L.P. gas (propane) price increases would reduce paybacks while the inclusion of high interest rates would extend them considerably.

As is apparent from the above example, the economic feasibility of an earth-tube system should be thoroughly investigated before beginning construction. While the heat savings can be calculated accurately, one should also give adequate weight (or value) to the estimated cooling benefits. Solar systems and heat exchangers provide no summer cooling while mechanical air conditioning has proved to be too costly. Earth tempering of ventilation air may be the least-cost alternative for providing tempered air during all times of the year.