GEOTHERMAL GREENHOUSE HEATING

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INTRODUCTION

Greenhouse heating is one of the most common uses of geothermal resources. Because of the significant heating requirements of greenhouses and their ability to use very-low-temperature fluids, they are a natural application. The evaluation of a particular greenhouse project involves consideration of the structure heating requirements, and the system to meet those requirements. This article, from the "Geothermal Direct Use Engineering and Design Guidebook", is intended to provide information on each of these areas.

GREENHOUSE CONSTRUCTION

In order to make an evaluation of geothermal heating systems for greenhouses, it is first necessary to examine the different heating requirements imposed by various construction methods.

At one time, greenhouses were constructed exclusively of cypress wood frames and single glass lites. Recent years have seen substantial changes in construction techniques and materials. In general, construction may be considered to fall into one of the following four categories:

1. Glass
2. Plastic film
3. Fiberglass or similar rigid plastics
4. Combination of two and three.

All of the above are generally constructed of steel or aluminum frames.

Glass greenhouses are the most expensive to construct because of both the cost of the glazing material and the requirement for a stronger framework to support the glass. In many cases, fiberglass panels are employed on the side and end walls of the structure. The building profile is generally of peaked design, with 36 and 42 ft widths, and lengths in 20 ft increments most common. This type of greenhouse is preferred by growers whose plants require superior light transmission qualities. In addition to offering the highest light quality, the glass greenhouse also has the poorest energy efficiency. Heating costs are high because of the poor insulating quality of single glazing and the high infiltration of cold air through the many "cracks" in the construction. This issue of high transmission loss has been addressed in recent years through the introduction of new, double glazing panels for glass houses. However, because of the expense of these panels and their effect upon light transmission, most glass greenhouses remain single layer.

Plastic film greenhouses are the newest variation in greenhouse construction techniques. This type of structure is almost always of the arched roof or "quonset hut" design. The roof can come all the way down to the ground or can be fitted with side walls. The side walls, if employed, and end walls are generally of fiberglass construction. Maintenance requirements for the plastic film are high in that it generally requires replacement on 3-year intervals or less, depending on the quality of the material. Most plastic film houses employ a double layer of film separated by air space. The air space is maintained by a small blower that pressurizes the volume between the layers. This double poly design is a very energy efficient approach to greenhouse design. Double poly not only reduces transmission losses (losses through the walls and roof) by 30 to 40%, but also substantially reduces infiltration (in leakage of cold air). Although the plastic film tends to lose more heat than glass through radiation, the net effect is a reduction in heating requirements compared to glass construction. Infiltration is reduced because the "cracks" present in other types of construction are eliminated through the use of the continuous plastic film. As a result, there is less opportunity for the cold outside air to penetrate the structure. The superior energy efficiency of the film construction comes at the price of reduced light transmission, however. As a result, highly light sensitive crops cannot be grown in the double-poly greenhouse as successfully as in other constructions. These greenhouses are generally constructed in 30 ft width and 100 and 150 ft lengths.

Fiberglass greenhouses are similar in construction to the glass houses described above. They are generally of peaked roof design, but require less structural support as a result of the lower weight of the fiber glass. Heat loss of the fiberglass house is about the same as the glass house. Although the fiberglass material has a lower conductivity than glass, when considered in the overall building heat loss, this has little effect.

HEATING REQUIREMENTS

In order to select a heating system for a greenhouse, the first step is to determine the peak heating requirement for the structure. Heat loss for a greenhouse is composed of two components: (a) transmission loss through the walls and roof, and (b) infiltration and ventilation losses caused by the heating of cold outside air.

To evaluate transmission loss, the first step is to calculate the surface area of the structure. This surface area should be subdivided into the various materials employed, i.e. square feet of double plastic, square feet of fiberglass, etc.

For example, consider a fiberglass wall, double-poly roof greenhouse 42 ft x 120 ft with 8 ft side walls (see Figure 1).

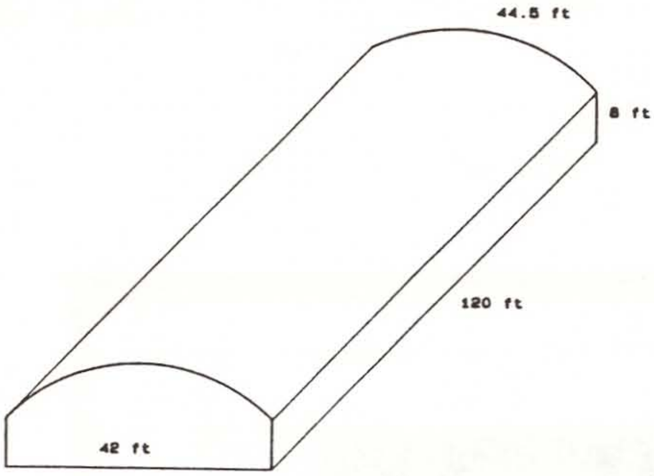


Figure 1. Example greenhouse.

Determine the double poly area (roof only):

A_1 = arch width x greenhouse length
A_1 = 44.5 ft x 120 ft
A_1 = 5,340 ft^2

Fiberglass area (side walls and end walls),
Side walls:

A_s = height x length x 2
A_s = 8 ft x 120 ft x 2
A_s = 1,920 ft^2

End walls:

A_e = 2 x [(height x greenhouse width) + (0.165* x greenhouse width^2)]
A_e = 2 x [(8 ft x 42 ft) + (0.165 x (42 ft)^2)]
A_e = 1,232 ft^2

* may vary slightly with different arch designs

Total fiberglass area:

$A_2 = A_s + A_e$
A_2 = 1,232 ft + 1,920 ft
A_2 = 3,152 ft^2.

After determining the total surface area (A) of the various construction materials, this value is then combined with a design temperature difference (ΔT) and a heat loss factor (U) for each component, to calculate the total transmission heat loss (q):

$$q = (A_1 \times \Delta T \times U_1) + (A_2 \times \Delta T \times U_2).$$

The design temperature difference is a function of two values: (a) design inside temperature, and (b) design outside temperature. The inside design value is simply the temperature to be maintained inside the space (usually in the 50 to 65°F range). The design outdoor temperature is not the coldest outdoor temperature recorded at the site. It is generally considered to be a temperature that is valid for all but 22 h/y during the heating season. Acceptable values for various locations are generally available from state energy offices or organizations such as American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE, 1978).

For this example, assume a design outdoor temperature of 0°F and a design indoor temperature of 60°F. This results in a design temperature difference (ΔT) of:

ΔT = 60°F - 0°F
ΔT = 60°F.

The final value in the transmission heat loss equation is the heat transfer coefficient (U). Acceptable values for various materials are shown in Table 1.

Table 1 Glazing Material U Values[a]

Material	Btu/h ft^2 °F
Glass	1.10
Fiberglass	1.00
Single poly	1.15
Double poly	0.70

a. Roberts, 1985

The U factor is also influenced by wind speed. The above values are based upon a wind speed of 15 mph. If other wind speeds are expected to occur at the design outside condition, then allowances should be made for this by adjusting the U factor are shown in Table 2.

Table 2 U Values at Various Wind Velocities

Material	Velocity (mph)					
	0	5	10	20	25	30
Glass	0.765	0.951	1.040	1.140	1.160	1.180
Fiberglass	0.695	0.865	.949	1.034	1.058	1.078
Single poly	0.810	1.000	1.090	1.190	1.210	1.230
Double poly	0.535	0.631	0.675	0.716	0.728	0.736

For the example, the transmission heat loss (q_p) for the double poly roof area is:

q_p = 5340 ft^2 x 60°F x 0.70 Btu/h ft^2 °F

q_p = 224,280 Btu/h

and for the fiberglass areas:

$$q_F = 3{,}152 \text{ ft}^2 \times 60°F \times 1.00 \text{ Btu/h ft}^2 \text{ °F}$$

$$q_F = 189{,}120 \text{ Btu/h}$$

Total transmission heat loss (q_1) is then:

$$q_1 = q_p + q_F$$

$$q_1 = 224{,}280 \text{ Btu/h} + 189{,}120 \text{ Btu/h}$$

$$q_1 = 413{,}400 \text{ Btu/h}$$

As mentioned previously, total heat loss is a function of two components: (a) transmission heat loss, and (b) infiltration. For greenhouse design, infiltration is generally analyzed via the air change method. This method is based upon the number of times per hour that the air in the greenhouse is replaced by cold air leaking in from outside. The number of air changes which occur is a function of wind speed, greenhouse construction, and inside and outside temperatures. Table 3 outlines general values for different types of greenhouse construction.

Table 3 Air Change Data for Various Glazing Materials

Material	Air Changes/h
Single glass	2.5 to 3.5
Double glass	1.0 to 1.5
Fiberglass	2.0 to 3.0
Single poly	0.5 to 1.0
Double poly	0.0 to 0.5
Single poly w/low fiberglass sides	1.0 to 1.5
Double poly w/low fiberglass sides	0.5 to 1.0
Single poly w/high fiberglass sides	1.5 to 2.0
Double poly w/high fiberglass sides	1.0 to 1.5

a. Roberts, 1985, ASHRAE, 1978.

As the number of air changes is related to the volume of the greenhouse, after selecting the appropriate figure from above, it is necessary to calculate the volume of the structure. For the example structure, this is most easily accomplished in two steps. These figures do not include ventilation.

Step 1 - volume (V_1) of the lower (rectangular) area of the greenhouse:

$$V_1 = \text{length} \times \text{width} \times \text{height}$$
$$V_1 = 120 \text{ ft} \times 42 \text{ ft} \times 8 \text{ ft}$$
$$V_1 = 40{,}320 \text{ ft}^3$$

Step 2 - volume (V_2) of the upper (arched) roof area of the greenhouse:

$$V_2 = \text{(area of arched section)(greenhouse length)}$$
$$V_2 = (0.165 \times W^2)\text{(greenhouse length)}$$
$$V_2 = (0.165 \times (42 \text{ ft})^2)(120 \text{ ft})$$
$$V_2 = 34{,}927 \text{ ft}^3$$

The total volume (V_T) of the greenhouse:

$$V_T = 34{,}927 \text{ ft}^3 + 40{,}320 \text{ ft}^3$$
$$V_T = 75{,}247 \text{ ft}^3$$

From the above table, the number of air changes/h (ACH) would be 1.0.

Heat loss (q_2) caused by infiltration:

$$q_2 = ACH \times V_T \times \Delta T \times 0.018$$
$$q_2 = 1.0 \times 75{,}247 \text{ ft}^3 \times 60°F \times 0.018$$
$$q_2 = 81{,}267 \text{ Btu/h}$$

Total greenhouse heating (q_T) requirement:

$$q_T = q_1 + q_2$$
$$q_T = 413{,}400 \text{ Btu/h} + 81{,}267 \text{ Btu/h}$$
$$q_T = 494{,}667 \text{ Btu/h (98.15 Btu/ft of floor area)}$$

This calculation assumes that infiltration will meet winter ventilation requirements. If artificial ventilation is required in excess of infiltration, this should be added to the peak load.

This is the peak or design heating load for the greenhouse. The heating equipment selected for the structure would have to be capable of meeting this requirement.

GREENHOUSE HEATING SYSTEMS

There are basically seven different geothermal heating systems which are applied to greenhouses:

1. Finned pipe
2. Unit heaters
3. Fan coil units
4. Soil heating
5. Cascading
6. Plastic tubing
7. Combination of the above.

Often the choice of heating system type is not dictated by engineering considerations such as maximum use of the available geothermal resource or even the most economical system, but on grower preference. Grower preference may be based strictly on past experience and familiarity with growing crops with that system. It may also be influenced by factors such as the type of crop, or potential disease problems. Some crops, such as roses and mums, require closely controlled humidity and a considerable amount of air circulation to prevent leaf mildew. If a radiant floor system is used, auxiliary circulating fans will be required. Tropical and subtropical potted plants, on the other hand, may require high humidity and higher soil temperatures. In this case, a radiant, under the bench system will be preferred, perhaps combined with an overhead air system for snow melting, and to get maximum sunlight during winter months in areas of high snow fall. Certain flowering plants may require shading to control blooming, thereby enabling the grower to market at the most opportune time. The type and location of the shading cover can affect the placement of heating and air handling equipment and, perhaps, the type of heating.

All these things should be taken into consideration and the heating system designer should maintain close communication with the grower in the selection of type and the placement of heating devices.

The following paragraphs outline the performance of the heating systems mentioned above.

Heat Exchangers

In most geothermal applications, a heat exchanger is required to separate actual heating equipment from the geothermal fluid. This is because of the scaling and corrosion associated with most geothermal fluids. Generally, the heat exchanger is placed between two circulating loops, the geothermal loop and the clean loop, as shown in Figure 2.

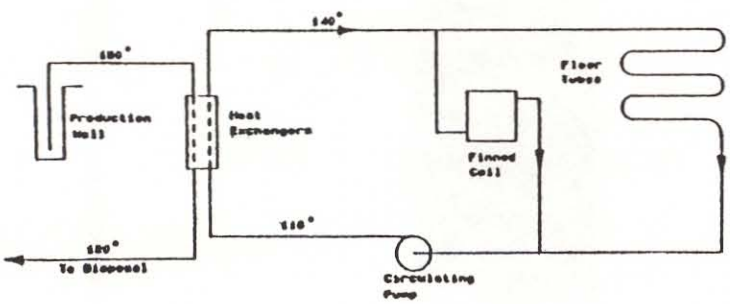


Figure 2. Heat exchanger schematic.

As a result of this heat exchanger, there is some loss in the temperature available for use in the actual heating equipment. This temperature loss depends upon the type of heat exchanger used. For plate-type heat exchangers, a temperature of 5 to 10°F should be applied, for shell and tube heat exchangers 15 to 20°F, and for homemade configurations 20 to 40°F. For example, assuming a geothermal resource temperature of 150°F is available, use of a plate heat exchanger would result in 140°F supply water, as shown in Figure 2.

Now that the heating requirement and supply water temperatures have been established, various heating systems can be evaluated with respect to their ability to meet this demand.

For geothermal applications, the available geothermal resource temperature has a large impact upon the system chosen. This is a result of the fact that certain types of heating methods yield better results with low-temperature fluid than others.

Finned Pipe

As the name implies, finned pipe is usually constructed of steel or copper pipe with steel or aluminum fins attached to the outside. These fins can either be circular, square or rectangular in shape. If the cover were removed from a hot water baseboard radiator in a home, a finned pipe would be found inside. In greenhouses, the heat requirement is much greater than in a house. As a result, larger pipes are used (1-1/4 in. or larger). In these sizes, the steel pipe with steel fins is most common.

Since most finned-pipe heating equipment used in geothermal projects was originally designed for standard hot water use, heating capacity is generally based upon 200°F or higher average water temperature and 65°F entering air temperature. If the available supply temperature from the geothermal system is less than the 200°F value, the capacity of the heating equipment, in this case finned pipes, will be less than the rated value. In addition, heating capacity of finned pipe, usually expressed in Btu/h per lineal foot, is influenced by fin size, pipe size and flow velocity. Table 4 shows one manufacturer's rating for equipment.

Table 5 shows the appropriate de-rating factors to be applied for average water temperatures of < 190°F.

Table 5 Derating Factors[a]

Average Water (°F)	Factor
180	0.80
160	0.62
140	0.47
120	0.30
100	0.17

a. Vulcan, 1971.

It is important to note that the capacity of this equipment is indexed to average water temperature, not supply water temperature. In order to find average water temperature (AWT), it is first necessary to calculate the temperature drop (ΔT), which is found according to the following relationship:

where

ΔT = temperature drop (°F)
q = heating requirement (Btu/h)
500 = constant, Btu/h gpm (°F)
Q = flow rate (gpm).
$\Delta T = q/(500 \times Q)$

Table 4 Steam and Extended Hot Water Ratings[a] (Bare Element)

Bare Heating Elements	Rows	Hot Water Ratings, Btu/h/lf Average Water Temperature							
		240°F	230°F	220°F	210°F	200°F	190°F	180°F	170°F
	1	1630	1480	1370	1240	1120	1010	900	790
33 fins/ft	2	2810	2570	2360	2140	1940	1760	1550	1370
	3	3660	3340	3080	2780	2520	2290	2020	1790
40 fins/ft	1	1750	1600	1470	1330	1220	1090	970	850
	2	2930	2670	2460	2220	2010	1830	1610	1430

a. Vulcan, 1971.

Using the greenhouse example from above, with a requirement of 494,667 Btu/h, assume a 150°F resource, a flow of 50 gpm, and the use of a plate-type heat exchanger.

ΔT = (494,667 Btu/h)/(500 Btu/h gpm °F x 50 gpm)
ΔT = 20°F

With a 150°F resource and a 10°F drop across the heat exchanger, this results in a 140°F supply temperature (T_s). Since a 20°F drop from supply to return was calculated, the average water temperature is then:

AWT = T_s - (ΔT/2)
AWT = 140°F - (20°F/2)
AWT = 130°F.

This provides the information required to select the necessary length of finned-pipe heating element required. Using Table 4, for a 2-in. steel element having 4-1/4 in. square fins spaced at 33/ft, output at 200°F AWT (factor of 1.00) is 1120 Btu/h lf. Using a correction factor of 0.385 from Table 5, actual capacity will be 0.385 x 1120 Btu/h lf = 431 Btu/h lf at the 130°F AWT.

With this value and the heating requirement of 494,667 Btu/h, calculate the length (l) of element required as:

l = (494,667 Btu/h)/(431 Btu/h lf)
l = 1,148 ft.

This large length requirement points up the limitation of finned pipe with respect to low temperature. As average water temperature falls below ~ 150°F, large lengths of finned element are required to meet the heating load in colder regions. As a result, finned pipe is not a particularly good choice for low-temperature resources.

Finned elements are generally installed along the long dimension of the greenhouse adjacent to the outside wall. Improved heat distribution is achieved if about one-third of the total required length is installed in an evenly spaced pattern across the greenhouse floor (ASHRAE 1978). This system has the disadvantage of using precious floor space that would otherwise be available for plants. In addition, it is less capable of dealing effectively with ventilation if it is required. Maintenance requirements are low, particularly if a heat exchanger is used. In addition, the natural convection nature of the finned pipe system does not increase electrical costs as a result of fan operation.

The costs for finned pipe elements are a function of the type and size of piping (steel or copper), and fin spacing (fins/ft). It is not possible to present costs for all combinations of these characteristics; however, Table 6 should serve to illustrate cost trends in fin pipe equipment.

Table 6 Comparative Costs of Finned Pipe Elements

Element	Cost/lf ($)
Copper/aluminum (3/4 in., 33 fin/ft)	4.00
Copper/aluminum (1 in., 33 fin/ft)	5.60
Copper/aluminum (1-1/4 in., 33 fin/ft)	8.25
Copper/aluminum (1-1/4 in., 40 fin/ft)	9.15
Steel/steel (2 in., 24 fin/ft)	8.05
Steel/steel (2 in., 33 fin/ft)	9.40

For labor cost estimating, a value of 0.25 to 0.35 man hours per lineal foot can be employed for finned pipe installation (Khashab, 1984).

Unit Heaters

Unit heaters consist of a finned coil and small propeller fan contained in a predesigned unit. These units are available in either horizontal or vertical configurations and are generally hung from the greenhouse structure at roof level. Air is discharged either directly into the greenhouse or into a perforated plastic distribution tube.

As with the finned pipe equipment, unit heaters are generally rated at 200°F entering water temperature (EWT) and 60°F entering air temperature (EAT). Changes in either of these two parameters will affect unit capacity (usually expressed in Btu/h). Since most geothermal resources applied to greenhouses are <200°F, some adjustment of unit capacity is necessary. Table 7 shows a typical set of manufacturer's performance data for unit heaters at standard conditions (200°F EWT/60°F EAT). To adjust for other conditions, Table 8 values are employed. It is important that the gpm values shown in Table 7 are met. Providing a unit with a flow less than that shown will decrease capacity.

Table 7 Hot Water Unit Heater Ratings[ab]

Model	Btu/h	GPM	CFM	Final Air Temp.	HP
A	90,000	9.0	1775	110	1/6
B	133,000	13.4	3240	100	1/3
C	139,000	14.0	2900	107	1/3
D	198,000	20.0	4560	102	1/2
E	224,000	22.0	4590	108	1/2
F	273,000	27.0	5130	108	1/2

a. Standard Conditions, 200°F EWT/60°F EAT.
b. Modine, 1979.

Because these units are generally constructed with copper tubes, even very small concentrations of dissolved hydrogen sulphide (H_2S) or ammonia (NH_3) will result in rapid failure. In addition, the long path through which the water must flow in the unit heater can result in scaling if the fluid has this tendency. As a result, a unit heater system should not be applied without an isolation heat exchanger.

Using information from the example greenhouse, unit heaters can be selected to meet the heating requirement. Example conditions are given in Table 9.

From Table 8, find a correction factor of 0.571. This factor is then applied to the capacity values shown in Table 7 to adjust them to the system conditions.

Table 8 Unit Heater Correction Factors[a,b]

EWT (°F)	EAT(°F) 40	60	80	100
80	0.293	0.143	-0-	-0-
100	0.439	0.286	0.140	0.069
120	0.585	0.429	0.279	0.137
140	0.731	0.571	0.419	0.273
160	0.878	0.714	0.559	0.410
180	1.024	0.857	0.699	0.547
200	1.170	1.000	0.833	0.684

a. To be applied to standard ratings.
b. Modine, 1979.

Table 9 Unit Heater Example Conditions

Condition	Value
Load	494,667 Btu/h
Resource temperature	150°F
Heat exchanger loss	10°F
Supply water temperature	140°F (150-10°F)
Greenhouse inside design temp.	60°F

For greenhouses over 50 ft in length, it is advisable to place unit heaters at each end to allow for better heat distribution. Assuming two units are used in this case, each would need a capacity (q) of:

q = (494,667 Btu/h)/2 = 247,334 Btu/h.

To convert this to an equivalent in Table 8, dividing by the above correction factor of 0.571:

q = (247,334 Btu/h)/0.571 = 433,158 Btu/h.

A two-unit system will not work because the largest unit capacity for a horizontal configuration is 273,000 Btu/h. The next step is to try a four-unit system--two-unit heaters at each end of the house. In this case, each unit would have a capacity of:

q = (433,158 Btu/h)/2 = 216,579 Btu/h.

This results in half the capacity calculated for the single unit above.

The proper selection would be the E unit at a capacity of 223,000 Btu/h. This is slightly more than the required 216,579 and will allow for a margin of safety in the design. As shown, the flow requirement (Q) for the four units will be:

Q = 22 gpm x 4 units = 88 gpm.

If the available flow rate is less than this value, unit capacity would have to be corrected for this reduced flow, possibly resulting in the need for additional units.

Two types of hot-water unit heaters are commonly used in greenhouse applications: horizontal and vertical. Of these two configurations, the horizontal unit is the more common. Vertical unit heaters are generally available in larger capacities than the horizontal units. In addition to the unit heater itself, a "poly tube" adapter is frequently required to attach the distribution system to the front of the heating device. Prices for each of these items are shown in Table 10. Capacities for unit heaters are based on 200°F entering water temperature.

Table 10 Horizontal and Vertical Unit Heater Costs[a]

Horizontal Unit Heaters		Vertical Unit Heaters	
Capacity[b] (MBH)	Cost ($)	Capacity[b] (MBH)	Cost ($)
27	425	72	460
45	510	88	510
73	565	123	550
106	595	140	600
160	775	220	840
255	1,005	297	1,055
293	1,085	408	1,420
		520	1,485

a. Means, 1990.
b. 1000 Btu/h.

Poly tube adapter costs are given in Table 11.

Table 11 Poly Tube Adapter Costs[a]

Size (in.)	Cost ($)
12	78
18	89
24	132

a. Means, 1986.

Fan Coil Units

These units are similar to the hot-water unit heater discussed previously. They consist of a finned coil and a centrifugal blower in a single cabinet. A few manufacturers carry their units in an off-the-shelf line designed specially for low temperature water. It is much more common that they are custom designed. The difference between the fan coil unit and the hot-water unit heater is primarily in the coil itself. In the fan coil system, the coil is much thicker and usually has closer fin spacing than the coil in a unit heater. Unit heaters generally have only a one or two row coil. A custom designed coil can have as many as six or eight rows. The additional rows of tubes create more surface area. The added surface area allows for more effective heat transfer, resulting in the ability to extract more heat from the water. To illustrate this, consider the unit heater selected in the previous section. Conditions are given in Table 12.

Table 12 Unit Heater Example[a] (two row)

Condition	Value
Capacity	127,904 Btu/h (0.571 x 224,000)
Air flow	4,590 cfm[b]
Water flow	22 gpm
Supply water temperature	140°F
Leaving water temperature	128.4°F
Leaving air temperature	85.8°F

a. Model E unit heater.
b. Cubic ft/min.

Supplying the same temperature water to a finned-coil unit with a four-row coil would result in the values as shown in Table 13.

Table 13 Fan Coil Unit Example[a] (four-row)

Condition	Value
Capacity	275,171 Btu/h
Air flow	4,590 cfm
Water flow	13.76 gpm
Supply water temp.	140°F
Leaving water temp.	100°F
Air in temp.	60°F
Air out temp.	115°F

a. Four-row coil with 11 fins/in., 2.5 ft x 3.67 ft.

Using only 60% of the water flow, the fan coil unit has the capability to more than double the heat output. In addition, the leaving air temperature is raised to 115°F from 85.8°F.

This benefit is not without cost, however. The fan coil units are generally larger and more bulky than the hot-water unit heater. As a result, they cost more. The larger coils discussed above generally require a larger fan motor to push the air through the added coil resistance. In this case, the unit heater would require a 0.5 horsepower (hp), motor and the fan coil unit would require a 1 hp motor. These factors may be compensated for by increased capacity, thus requiring fewer units.

Most importantly, the ability to extract more heat from each gallon of water pumped reduces well pumping requirements and allows the development of more greenhouse area, using the same resource. As a general rule of thumb, a properly designed fan coil can cool water down to within about 15 to 25°F of the same space temperature. For example, if a greenhouse is to be maintained at 60°F and the finned coils are supplied with water at 120°F, a system ΔT of 120°F - (60°F + 25°F), or 35°F could be achieved. If the well flow is known, then the total heat supplied (q) can be calculated as:

$$q = 500 \times gpm \times \Delta T = Btu/h.$$

This figure can then be compared to greenhouse heat loss to find the total area of greenhouse that can be developed.

The fan coil construction is very similar to that of the unit heater. For the same reasons, it is not recommended that they be applied without an isolation heat exchanger. The fan coil system is the most cost effective method for extracting large quantities of heat from very-low-temperature heating mediums.

Table 14 presents cost data for fan coil units.

Table 14 Fan Coil Unit Cost Data

Nominal Capacity (Btu/h)	Air Flow (cfm)	Cost ($)
120,000	2,000	1,240
240,000	4,000	1,665
360,000	6,000	2,320
480,000	8,000	2,970

As with the unit heater, a poly tube adapter would be required if this equipment is to be attached to such a distribution system. For prices, see unit heater section.

Soil Heating

This system generally involves using the floor of the greenhouse as a large radiator. Tubes, through which warm water is circulated, are buried in the floor of the greenhouse. Heat from warm water is transferred through the tube to the soil and, eventually, to the air in the greenhouse.

In the past, tube materials were generally copper or steel. Because of corrosion and expansion problems with these materials, nonmetallic materials have seen increasing application in recent years. The most popular of these is polybutylene. This material is able to withstand relatively high temperatures (up to ~ 180°F) and is available in roll form for easy installation. PVC piping is only available in rigid form and is limited with respect to temperature. Polyethylene and similar materials are available in flexible roll form, but are (as PVC) generally limited in terms of temperature handling ability.

A soil heating system is preferred by many operators because it results in very even temperature distribution from floor to ceiling and does not obstruct floor space or cause shadows. However, its ability to supply 100% of the heating requirements of a greenhouse necessitates a rather mild climate and a low inside design temperature. This is caused by the nature of heat transfer in the system. As heating requirements are increased, the required heat output from the floor is increased. In order to produce more heat, the floor surface temperature must be increased. Very quickly a point is reached at which it is difficult to spend extended periods on such a hot floor. In addition, if plants are grown on or near the floor (including benches), heat transfer to the plants may be excessive with a radiant floor system. As a result, this system is generally employed in conjunction with another system such as unit heaters. The floor system supplies the base load for the greenhouse and the secondary system is used for occasional peaking purposes.

The procedure for designing a floor system consists of:

1. Determining the heat load for the greenhouse.
2. Calculating the required floor temperature to meet the load.
3. Calculating the required size, depth and spacing of the tubes.

The load analysis portion of the procedure has been covered. The next step is to determine the required floor surface temperature.

The heat output of the floor (usually expressed in Btu/h ft^2) is a function of the floor surface temperature, greenhouse air temperature and average temperature of unheated surfaces in the room (AUST). Heat output from the floor occurs by two mechanisms: convection and radiation.

After the heat loss of the greenhouse has been calculated, it is divided by the area of the floor which will be used for heating purposes (usually about 10% less than the actual floor area). Using the previous greenhouse example, 42 ft x 120 ft, with a total heat loss of 494,667 Btu/h, the value for heat loss (q/A) is:

$$q/A = (494{,}667 \text{ Btu/h})/(42 \text{ ft} \times 120 \text{ ft} \times 0.90)$$
$$q/A = 109.1 \text{ Btu/h ft}^2.$$

This value is then used in the following equation to solve for the required floor surface temperature (ASHRAE, 1984):

$$q/A = 0.15[(tp + 460/100)^4 - (AUST + 460/100)^4] + (0.32(Tp - Ta)^{1.32} = 109.1 \text{ Btu/h ft}^2$$

where

Tp = floor surface temperature
Ta = indoor air temperature.

Before the above can be solved for TP, a value for AUST must first be calculated. As mentioned earlier, AUST is the area weighted average temperature of unheated surfaces in the room. For a greenhouse, these surfaces are the walls and roof.

Inside surface temperature can be calculated according to the formula below. Referring back to the heat loss example, the greenhouse is constructed of both double poly (roof) and single fiberglass (walls). The calculation for AUST is:

$$IST = IDT - |[0.595/(1/U)] \times \Delta T|$$

where

IST = inside surface temperature (°F)
IDT = inside design temperature (°F)
U = glazing material U-factor, Btu/h ft^2 (°F)
ΔT = design temperature difference (°F).

For the example greenhouse, the inside surface temperature of the double poly roof area is:

$$IST = 60°F - [(.595/(1/.70) \times 60°F]$$

$$IST = 35.0°F.$$

The inside surface temperature for the single fiberglass area is:

$$IST = 60°F - |[0.595/(1/1.0)] \times 60°F|$$

$$IST = 24.3°F$$

$$AUST = (A_1 \times IST_1 + A_2 \times IST_2)/(A_1 + A_2)$$

$$AUST = \frac{(5{,}340 ft^2 \times 35°F) + (3{,}152\ ft^2 \times 24.3°F)}{(5{,}340\ ft^2 + 4{,}352\ ft^2)}$$

$$AUST = 31.1°F$$

This value can now be inserted into the equation for floor temperature developed by ASHRAE as:

$$q/A = 0.15[(Tp + 460/100)^4 - (31.1 + 460/100)^4] + (0.32(Tp - 60)^{1.32} = 109.1 \text{ Btu/h ft}^2$$

Solving for Tp:

$$Tp = 103°F.$$

This means that in order to meet the peak demand, a floor surface temperature of 103°F would be required. Plants could not be grown in or near such warm soil. In addition, the amount of time that workers could be exposed would be limited. As a result, it would be advisable to supply a portion of the design capacity with this system and the rest with a secondary system. If the system is designed for only 60% of peak requirements (65.5 Btu/ft^2), a floor temperature of only 84°F would be required. This figure is close to the maximum recommended floor surface temperature of 85°F for occupied areas. If the greenhouse is occupied only for brief periods, this value can be exceeded somewhat. A secondary system would be used for peaking.

The next step is to determine the depth and spacing of the tubes supplying the heat. Tube spacing and size is dependent upon the available water temperature. Generally, depth is more a function of protecting the tubes from surface activity than system design, and a figure of 2 to 6 in. below the surface is common.

Since it is the purpose of the floor panel system to use the floor as a large radiator, it follows that the installation of the tubing should result in as uniform a floor surface temperature as possible. This is accomplished by two general approaches: (a) placing smaller diameter tubes at close spacing near the surface of the floor, or (b) placing larger tubes spaced further apart at a greater burial depth. The theory behind this approach is to reduce the difference between the distance heat must travel vertically (from the tube to the surface directly above it) and laterally (from each tube to the surface between the tubes)(Adlam, 1947).

The depth at which the tubes are to be buried is often a function of protecting them from surface activity. For burial in the soil floor of a greenhouse, a depth of at least 2 to 3 in. should be employed. If crops are to be grown directly in the soil, depth requirements are such that this type of system becomes impractical.

Tubing size is a function of heating requirements. Common sizes are 1/2 in., 3/4 in. and 1 in. with the smaller sizes used generally in the 2 to 4 in. depth and the larger lines for depths of 5 in. and greater.

The final determination of the size and spacing is a function of heat output (Btu/ft^2) required, mean water temperature, soil conductivity, and burial depth.

The required heat loss is fixed by the type of greenhouse construction used. Soil conductivity is also fixed by site characteristics. As mentioned earlier, the minimum burial depth is fixed by surface activity. As a result, the choice of size and spacing is balanced against mean water temperature, the single parameter over which the designer has some control. Table 15 lists some maximum mean water temperatures for various situations. Employing mean water temperatures above these values will result in floor surface temperatures >90°F. If workers are to spend extended periods in the greenhouse, floor surface temperatures above this value would be unacceptable.

Table 15 Maximum Recommended Mean Water Temperatures(°F)

Burial Depth (in.)	Steel Pipe k=6	Steel Pipe k=9	Polybutylene Tube k=6	Polybutylene Tube k=9
1	111	105	124	112
2	116	110	131	120
3	122	115	139	128
4	125	117	144	131
5	128	120	148	135
6	134	125	156	142

a. k = soil conductivity in Btu x in./ft^2 x °F x h.

In addition to the maximum mean water temperature, it is also important when making this calculation to be aware of system ΔT (supply temperature minus return water temperature) and its impact upon system design. Temperature drops above ~ 15°F should employ a double serpentine to balance the circuit output. For ΔT below 15°F, a single serpentine can be used as shown in Figure 3.

Using the heating requirement and floor surface temperature calculated above, some combinations of tubing size and spacing can be determined. It will be assumed that, because of surface activity, the tubes would have to be buried a minimum of 3 in. below the surface. Soil conductivity is 9 Btu in./h ft^2 °F. Resource temperature is 140°F and a flow of 60 gpm is available. Polybutylene tubing will be employed. Plate heat exchanger loss is 7°F.

As a result of the heat exchanger loss, 133°F fluid will be available for supply. If the entire flow is used, the system ΔT would be:

$$\Delta T = (196{,}800 \text{ Btu/h})/(500 \text{ Btu/h gpm °F} \times 60 \text{ gpm}) = 6.6\text{°F}$$

The resulting mean water temperature (Tw) would be:

$$Tw = 133\text{°F} - (6.6\text{°F}/2) = 130\text{°F}$$

This value is close to the recommended maximum mean water temperature found in Table 15, so design can proceed. If this value had been above the recommended temperature, either the tubes would have to be buried deeper or the radiant floor system operated at a lower supply-water temperature.

Subtracting the required floor surface temperature from the mean water temperature results in the tube-to-surface temperature difference. Using this and the value from Figure 4, the heat output per lineal foot (lf) of tube can be determined. From Figure 4, for a burial depth of 3 in., a value of 1.40 Btu/h lf °F for 3/4 in. tubing results. For 1 in. tubing, the value would be 1.87 Btu/h lf °F.

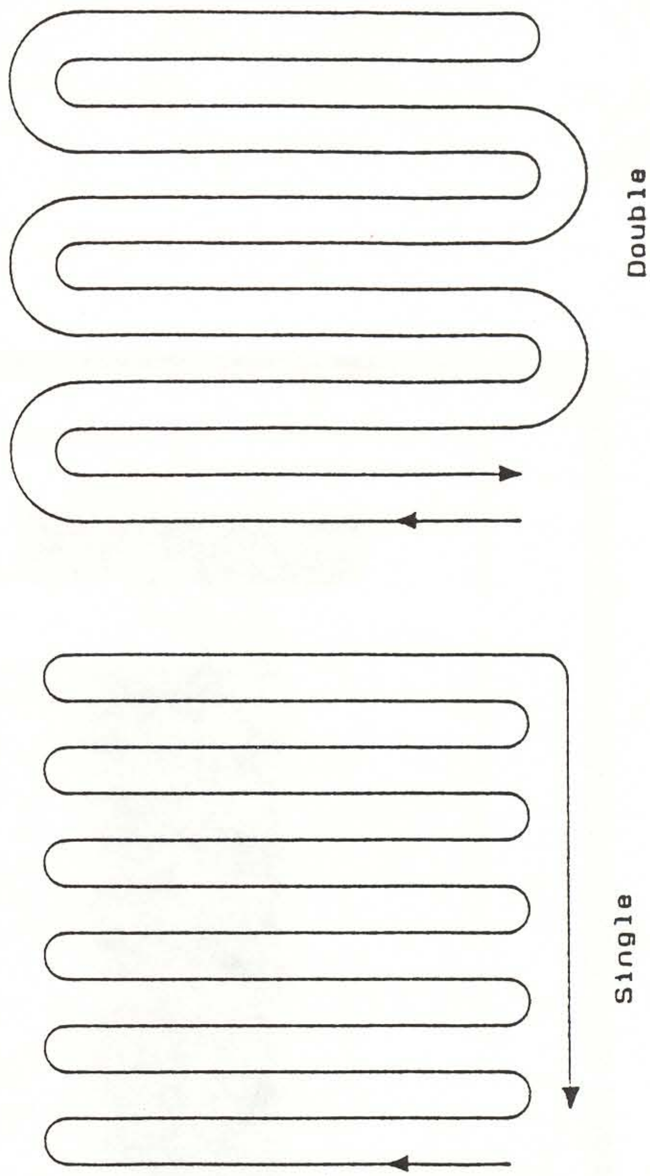
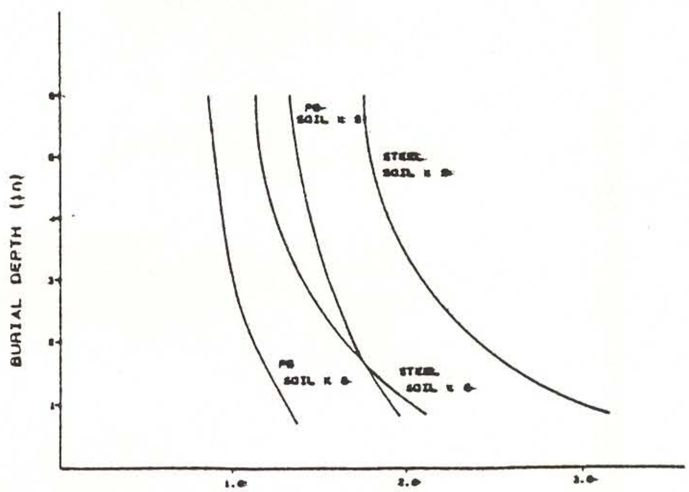


Figure 3. Single and double serpentine piping layout.



3/4" tube output (Btu/hr•lf•°F) x axis title

Figure 4. Heat output for radiant floor system.

The heat output per lf for each of these tubes would be arrived at by multiplying the Btu/hr•lf•°F value times the tube-to-surface temperature difference.

For 3/4 in. tube: 1.4 x (128°F - 84°F) = 61.6 Btu/h lf

For 1 in. tube: 1.87 x (128°F - 84°F) = 82.3 Btu/h lf

The tube spacing is determined by dividing the tube output per lineal foot into the heating requirement (per square foot).

For 3/4 in. tube: (65.5 Btu/ft^2 h)/(61.6 Btu/h lf) = 1.06 lf/ft^2

For 1 in. tube: (65.5 Btu/ft^2 h)/(82.2 Btu/h lf) = 0.80 lf/ft^2.

Taking the inverse of the above results and multiplying by 12 in./ft yields tube spacing:

For 3/4 in. tube: (1/1.06) x 12 = 11.3 in.
For 1 in. tube: (1/0.80) x 12 = 15.0 in.

In most cases, because of losses downward and at the edges, a safety factor of 10 to 15% is added to the tube requirements. This is most conveniently accomplished by reducing the tube spacing by 10 to 15%.

In order to demonstrate the sensitivity of the system to other parameters, Table 16 shows some additional tube spacing calculations that are made:

Table 16 Tube Spacing (in.)

				Tubing	
	Soil k	Depth	MWT	3/4 in.	1 in.
Base case	9	3	128	11.3	15.0
	6	3	128	8.1	10.8
	9	6	128	10.2	13.6
	6	3	118	8.9	11.8
	6	6	118	5.4	7.2

Using the base case tube spacing and 3/4 in. tubes, a total of 4,818 ft of tubing will be required. In order that a reasonable pressure drop will be attained, the total 60 gpm flow would be divided among a number of individual circuits. At a velocity of approximately 3 ft/s, each circuit would carry 5 gpm. This would require 14 circuits for the total flow. If the 1 in. tubing is used, a smaller number of higher flow circuits could be employed.

As suggested above, a heat exchanger is used in this case. This is for two reasons: protection from scaling and control of temperature.

Control of temperature is the most critical. The only method of controlling the output of a floor system is by controlling the water temperature in the tubes. The use of a heat exchanger allows this control to be carried out more easily. The flow of geothermal fluid to the exchanger is regulated to maintain a given supply temperature to the heating loop as shown in Figure 2.

As suggested in the example, a great deal of piping material is required to supply just 60% ofthe peak requirement of a greenhouse in a cold location. In addition, the inability to grow directly in or on the soil surface also restricts the wide acceptance of this type of system.

The cost of both polybutylene and polyethylene piping is a function of pipe size and the standard dimension ratio (SDR). The SDR is related to the nominal pipe size divided by the wall thickness, or as the SDR increases, the wall thickness decreases. Material costs shown in Table 17 are for SDR 11. This material is rated at 100 psi at 180°F (polybutylene) and 160 psi at 70°F (polyethylene).

Table 17 Polyethylene and Polybutylene Pipe Costs (Means, 1990)

Size (in.)	Polybutylene ($/lf)	Polyethylene ($/lf)
1/4	0.13	-
3/8	0.15	-
1/2	0.16	-
3/4	0.29	0.13
1	0.49	0.20
1-1/4	0.70	0.34
1-1/2	0.99	0.46
2	1.66	0.77

Cascading

This method, which was developed by the Soviets for waste heat applications, involves distributing water over the outside of the greenhouse in a thin "sheet" of flow. Although this is a very effective method of heating a greenhouse, there are some disadvantages that would limit its use in geothermal applications.

Distributing large quantities of warm water over a surface exposed to the atmosphere results in substantial energy losses. These losses exceed by many times the requirements of the greenhouse. As a result of the large heat losses from the cascaded fluid, a great deal of evaporation takes place. Because of the many chemical species contained in geothermal fluids, evaporation would tend to cause concentration and subsequent deposition of these constituents on greenhouse surfaces.

Because of these disadvantages, it is unlikely that such a system would be applied to any great extent in the U.S. Therefore, it will not be discussed here.

Bare Tube System

This system involves the use of bare tubing, usually small diameter polybutylene or similar material. The tubing is installed either on the floor or suspended under benches. It is preferable for the tubing to be located low in the greenhouse, although a portion may be located overhead. Regardless of the installation location, it is very important that the tubing be arranged such that each tube is separated from the others. If the tubes are bunched together, the effective surface area of each is reduced, thus lowering heating capacity.

In colder regions, this system encounters the same problem as the floor panel system in that large quantities of tubing are required to meet the design requirement.

Control of the system in many cases has been manual by way of gate valves. However, as with the floor panel system, the use of a heat exchanger can allow accurate control of temperature and, hence, output.

Design of a system is based upon the average water temperature of the heating loop. For a system using a heat exchanger:

1. Determine the flow of geothermal fluid available. We will assume 80 gpm at 150°F for the example case.

2. Calculate the greenhouse heat loss; i.e., 494,667 Btu/h for the example.

3. Determine the temperature drop in the available water flow:

   $\Delta T = q/(500 \times gpm)$
   $\Delta T = (494{,}667 \text{ Btu/h})/(500 \text{ Btu/h gpm °F} \times 80 \text{ gpm})$
   $\Delta T = 12.4°F.$

4. Determine heating loop average water temperature (AWT) using:

   $Ts = Tg - 10°F$

   where

   Ts = supply temperature (°F)
   Tg = geothermal resource temp. (°F)
   $Ts = 150°F - 10°F$
   $Ts = 140F$

   $AWT = Ts - (AWT/2)$
   $AWT = 140°F - (12.4°F/2)$
   $AWT = 134°F$

5. Calculate heat output per foot of tubing based on the average water temperature (Heilman, 1929) (AWT) using:

   $$q/l = |[1.016 \times (1/D)^{0.2} \times (1/T_{avg})^{0.181} \times (\Delta T^{1.266})] + (15.7 \times 10^{-10}) \times (T1^4 - T2^4)| \times (ft^2/lf \text{ pipe})$$

   where

   D = tube diameter (in.)
   $T_{ave} = 460 + (AWT - T_{air})/2$ (°F)
   $\Delta T = AWT - T_{air} + 3°F$ (°F)
   $T_1 = 460 + AWT$ (°F)
   $T_2 = 460 + T_3$ (°F)
   $T_3 = (AUST + T_{air})/2$ (°F)

   Using a 3/4 in. tube, 60°F air temperature and 134°F AWT, Btu/h lf for the example case:

   $$|[1.106 \times (1/1.05)^{0.02} \times (1/557)^{0.181} \times (71)^{1.266}] + (15.7 \times 10^{-10}) \times [(594)^4 - (505)^4]| \times (0.275)$$

   $q/l = 45.2$ Btu/h lf

The total length (l) required to meet the design load becomes:

$l = g/(g/l)$
$l = (494{,}667 \text{ Btu/h})/(45.2 \text{ Btu/h lf})$
$l = 10{,}944$ lf

This length requirement can then be compared to requirements for other tubing sizes and water temperatures to determine the most economical system.

Costs for polybutylene and polyethylene piping used in the bare tube system are shown under the previous section.

The procedures presented in this chapter are intended to familiarize the reader with some of the considerations appropriate to greenhouse heating systems. It is strongly recommended that the services of a consulting engineer be retained for final design purposes.

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