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ABSTRACT

This module on solar system design fundamentals is one of six in a series intended for use as supplements to currently available materials on solar energy and energy conservation. Together with the recommended texts and references (sources are identified), these modules provide an effective introduction to energy conservation and solar energy technologies. The module is divided into these sections: (1) set of objectives: (2) programed instructional material, consisting of short readings describing ideas and techniques one step at a time, and a question or problem on each reading: (3) review questions and answers at intervals; and (4) posttest. Objectives for this module are for the student to be able to describe examples of basic types of solar heating systems, outline three major steps in design of a solar heating system, and perform each of those three major steps. (YLB)

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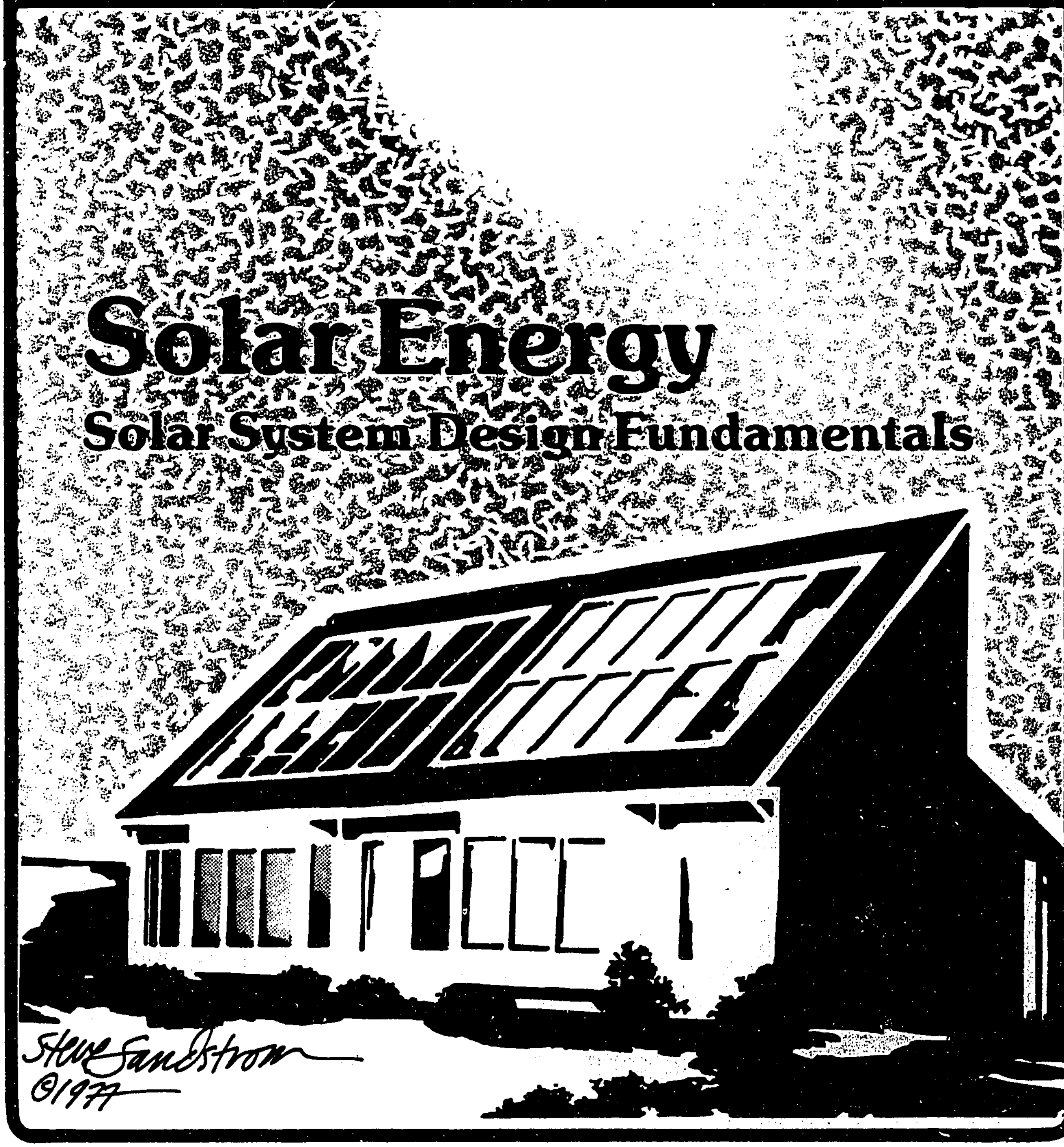
INDIVIDUALIZED LEARNING SYSTEMS

Solar Energy

Solar System Design Fundamentals



INSTRUCTIONAL LEARNING SYSTEMS

Solar Energy

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Introduction

These modules are intended to be used as supplements to currently available materials on solar energy and energy conservation. The two best available texts are

Leckie, Masters, Whitehouse and Young; Other Homes and Garbage, Sierra Club Books, 1975

and

Anderson, The Solar Home Book, Cheshire Books, 1975.

There are several reference works that would also be very useful to have on hand. The three most useful ones are

ASHRAE Guide and Data Book, Handbook of Fundamentals, American Society of Heating, Refrigeration and Air Conditioning Engineers, New York, 1977.

U.S. Department of Commerce, Climatic Atlas of the United States, Environmental Data Service, Reprinted by the National Oceanic and Atmospheric Administration, 1974.

U.S. Department of Commerce, Monthly Normal of Temperature, Precipitation and Heating and Cooling Degree-Days (1941-1970) National Oceanic and Atmospheric Administration, Climatography of the United States (by state).

The last two references can be obtained from the National Climatic Center, Environmental Data Service, Federal Building, Asheville, NC 28801. The most important data to have on hand are the percent possible sunshine and heating degree-day records for locations in Oregon. They're available in the last two references. Some data are also available in the two texts and the modules themselves.

The modules are designed to simplify and supplement the treatment of some of the subjects discussed in the texts and references. In combination, the modules, texts, and references provide an effective introduction to energy conservation and solar energy technologies.

The technique you'll use to learn the skills presented in this module is called programmed instruction. It's a technique which we think will enable you to learn these new skills quickly and easily.

The module is divided into several sections:

1. A list of objectives, which tells you what you should expect to learn from this module.
2. Programmed instructional material which we'll describe later on in this introduction.
3. A post-test, which will help you find out what you were able to learn by using the module.
4. A student evaluation form which you can use to tell us what you liked and disliked about the module, so we can make it better for students who use it later on.

The programmed part of the module consists of short readings which show you the ideas and techniques you need a step at a time. Most are followed by a question or problem which gives you a chance to review what you just read. Depending on your answer to the question or problem, you'll be guided to another short reading which will either help you review a little more, or introduce you to a new idea or technique. Each short reading is called a frame.

To get the most out of the programmed part, you need to follow the directions exactly. Resist any temptations to skip around, and respond in the best way you can to the question in each frame before moving on to the frame you're told to read next.

It'll help to have pencil, paper, and a pocket calculator handy for some of the computations you're asked to do.

Don't forget about your instructor. You don't have to do it all by yourself. Ask for help with any part of the module that you can't get through by yourself. Good luck!

OBJECTIVES

Overall Objective 1:

The student will be able to describe examples of the basic types of solar heating systems.

Sub-Objectives:

The student will be able to list the main features and give an example of

A. an active solar heating system.

B. a passive solar heating system.

Overall Objective 2:

The student will be able to outline the three major steps in the design of a solar heating system.

Overall Objective 3:

The student will be able to perform each of the three major steps in the design of a solar heating system.

Sub-Objectives:

For various types of active and passive solar systems, the student will be able to compute the required:

A. collector size.

B. heat storage volume.

C. pump or fan size.

1. Solar heating systems can be divided into two types. The two types are usually called _active_ and _passive_.

Active systems use forced convective heat transfer to move solar heat from separate solar collectors to heat storage containers and the spaces to be heated. The solar collector, heat storage container, and the space to be heated are separated in space and usually thermally insulated from each other.

Passive systems almost always combine the collector, heat storage, and heated space in one location. They don't use forced convective heat transfer to move heat from place to place. They use either free convection or radiation.

Solar heating systems that use solar collectors to heat water or air which is circulated by pumps or fans are active systems. Houses which use solar heat passing through windows to heat water drums, rocks, concrete floors or walls are passive systems. Solar water heaters that use directly illuminated hot water tanks instead of the typical flat plate solar collector are also passive systems.

State the differences between active and passive solar heating systems in your own works Check your answer in frame 2.

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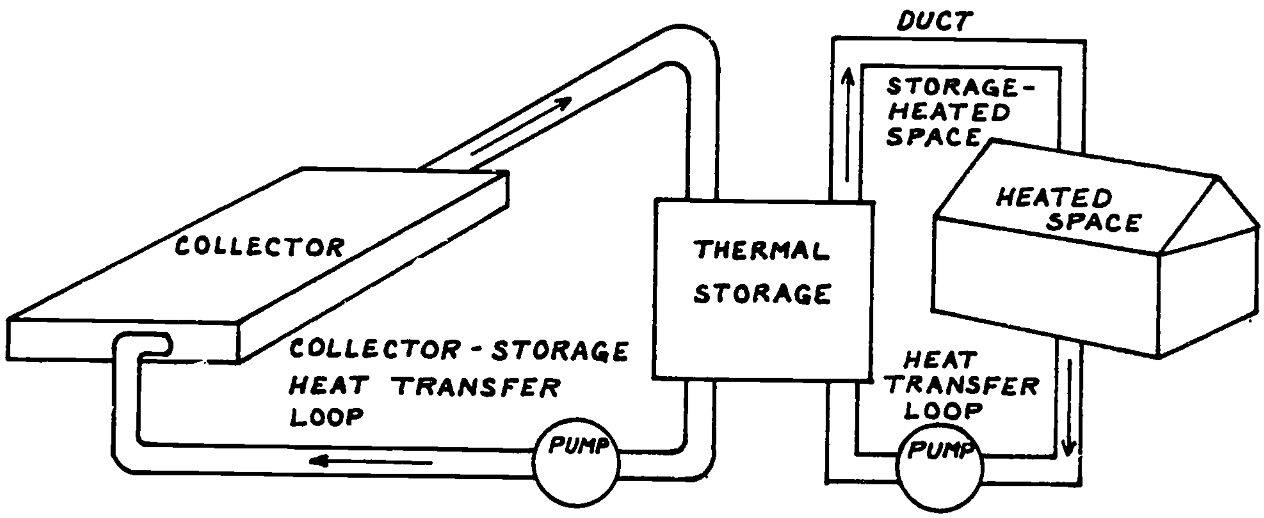
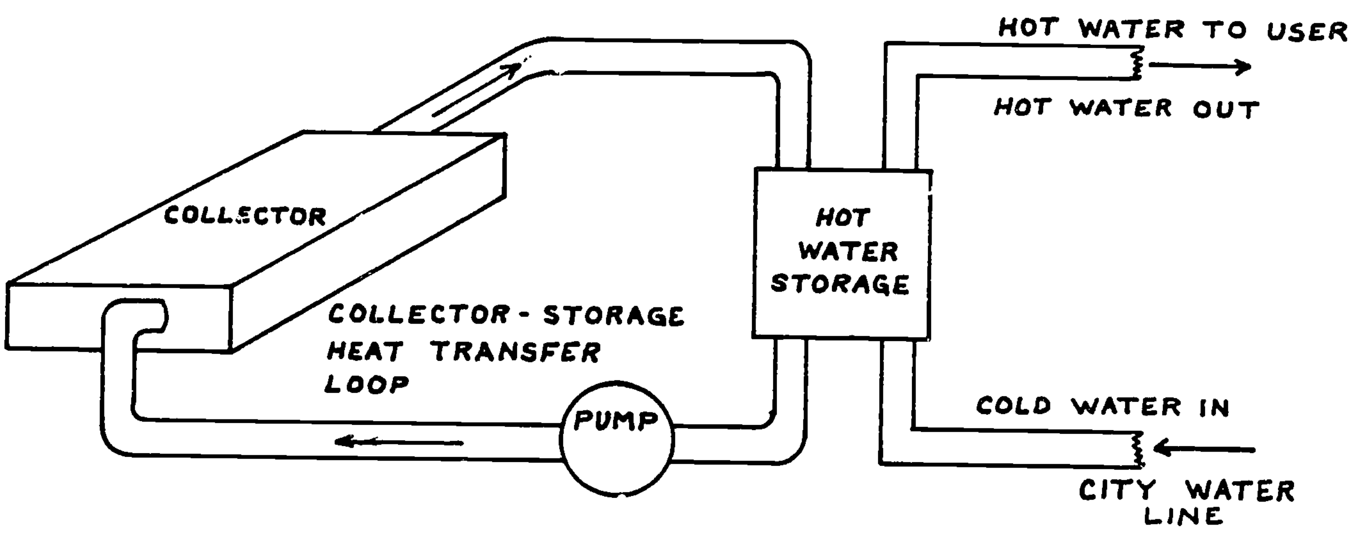
2. Active systems have separated collector, thermal storage, and heated space. They also move heat from place to place by forced convection (fans or pumps).

Passive systems usually combine collector and storage and move heat by radiation or free convection. Go on to frame 3.

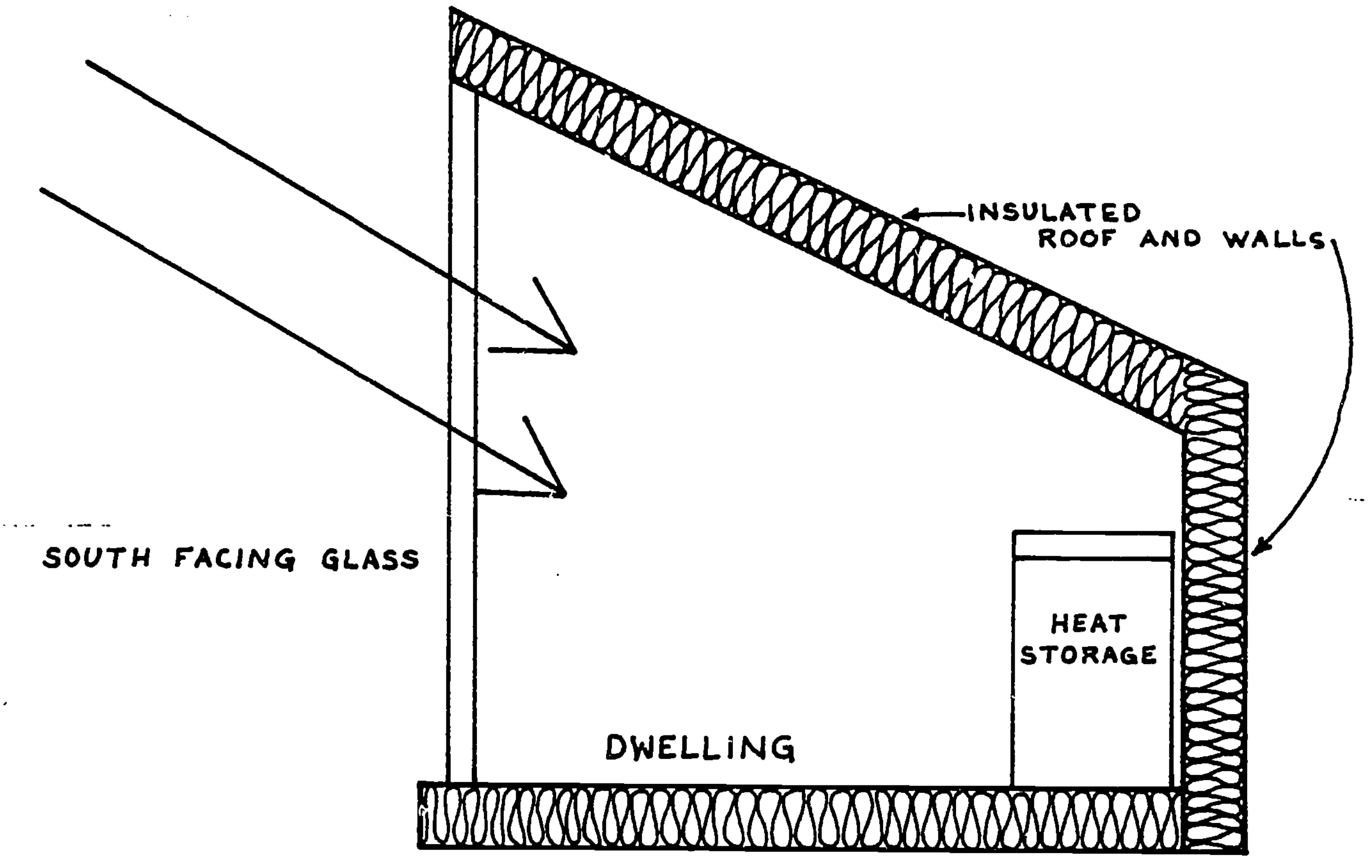
AN ACTIVE SOLAR SPACE HEATING SYSTEM



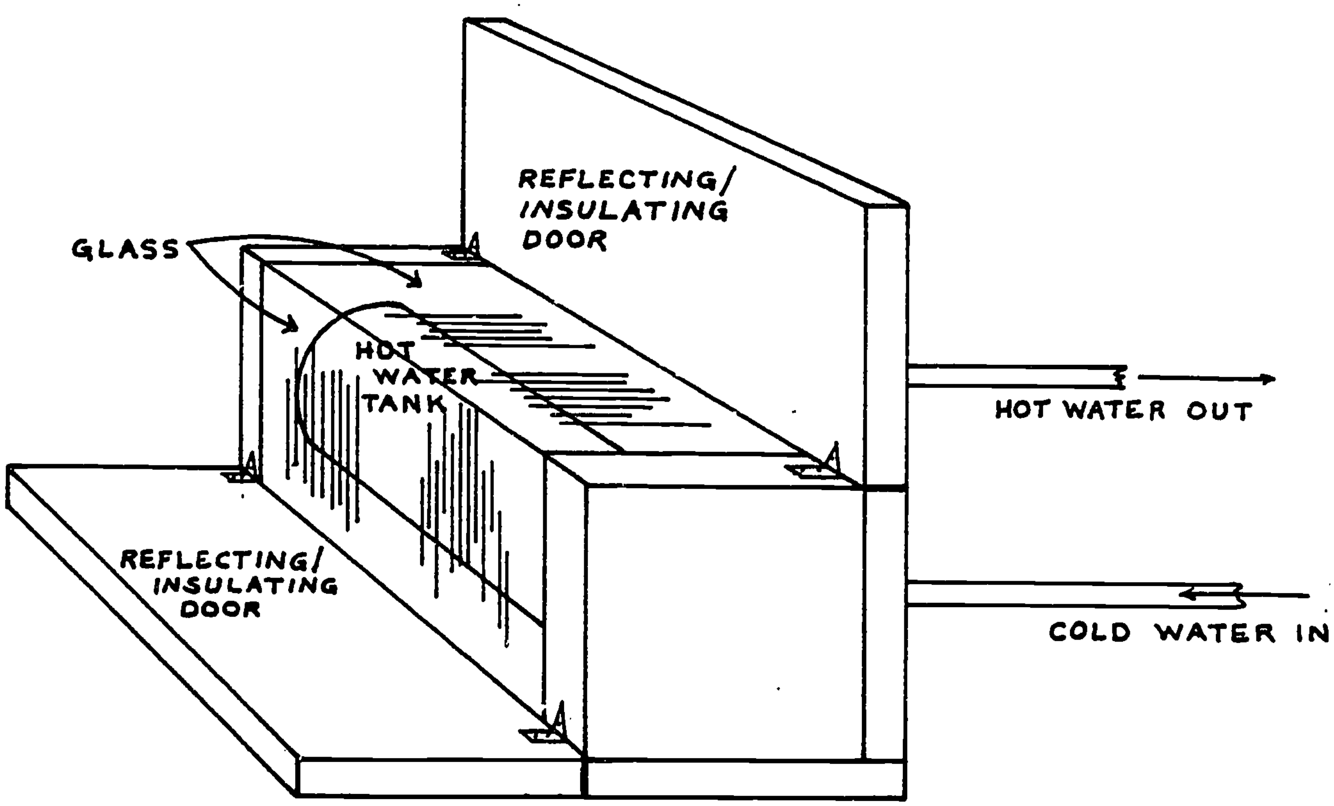
AN ACTIVE SOLAR HOT WATER HEATING SYSTEM



A PASSIVE SOLAR SPACE HEATING SYSTEM



A PASSIVE SOLAR HOT WATER HEATING SYSTEM



3. Whether you choose an active or a passive solar heating system will depend on how the system will be used, and whether or not it's convenient to combine the collector, the heat storage, and the heated space. Your choice of the sizes of the system parts will depend on your estimates of how much heat will be required, how much can be collected from the sun, and how long heat must be stored.

In this module, you'll learn how to estimate tne sizes of system parts for both active and passive solar systems. The estimates you'll learn to make will be based on approximate weather data. Because of our inability to predict future weather, it's wise to allow a 10 to 20% safety margin in your estimates of collector size and heat storage capacity. That'll make it more likely that you'll get the amount of solar heat you hope for, even during years of unusually bad weather. Go to frame 4.

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4. The most important and difficult thing to estimate in a solar system is the glass or solar collector area required to collect the desired amount of heat. The estimate depends on three factors: the amount of heat required, the amount of solar heat available, and the efficiency of the system collecting the heat. The commonly available weather data only allow you to estimate the first two factors over periods of days or months.

The system efficiency also depends on the weather. It will vary with the amount of solar radiation, the temperature of the solar collector, and the outside temperature. All three of those things will change with the hourly changes in the weather, the temperature of the heat storage container and the temperature of the heat transfer fluid.

There are computer programs and detailed computation procedures which can give approximate estimates of system efficiency based on monthly weather data and general knowledge of the design of the system. The ones now in existence only apply to active systems. The results of the computations indicate that active space heating system heat collection efficiencies range from about 25% to about 30%. 25% is a pretty safe estimate of active solar space heating system efficiency. Active hot water heating system efficiencies average about 50%. Swimming pool heating system efficiencies average between 60% and 70%.

List the three factors which determine the size of the solar collector in an active solar heating system. Check your answer in frame 5.

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5. The factors are the amount of heat required, the amount of solar radiation available, and the heat collecting efficiency of the system.

The collector size can be estimated quickly if estimates of all three factors are available. The first step is to estimate the amount of solar heat collected per square foot of collector.

You first find the total amount of solar radiation falling on one square foot of collector during the entire period of the estimate. If the period is a month, you multiply the average intensity for the month in BTU/Ft.^{2}-Day by the number of days in the month. If the period includes several months, you find the monthly totals and add them.

The most effective procedure is to find the total radiation for the entire heating season. If you're sizing a water heating system, you'll need to have the total for the entire year. If you're sizing a space heating system, save all the monthly totals for later use in sizing the heat storage system.

Once you have the total amount of solar radiation falling on one square foot of collector for the heating season, you can estimate the amount collected per square foot by multiplying by the estimated efficiency. The efficiency should be written as a decimal (%/100). For example, 25%

efficiency should be written as .25. Write down estimates of the efficiencies of all three types of solar heating systems and check your answers in frame 6.

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6. Space heat — 25% to 30% (.25 to .3)

Water heat — 50% (.5)

Pool water heat — 60% to 70% (.6 to .7)

In Corvallis, the solar radiation intensity figures for the space heating season on a 60^o tilted solar collector are:

October	1149 BTU/Ft.^{2}-Day
November	648 BTU/Ft.^{2}-Day
December	423 BTU/Ft.^{2}-Day
January	688 BTU/Ft.^{2}-Day
February	766 BTU/Ft.^{2}-Day
March	1032 BTU/Ft.^{2}-Day
April	1141 BTU/Ft.^{2}-Day

Find the total amount of solar heat collected over the heating season by a solar space heating system with an efficiency of 25%. Check your answer in frame 7.

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7. Just take the monthly averages, and multiply by the number of days in the month to get the monthly totals. Then add the monthly totals and multiply by the efficiency to get the total collected. Here's a table:

Month	Intensity (BTU/Ft.^{2}-Day)	Number of Days	Total (BTU/Ft.^{2})
Oct.	1140	31	35,619
Nov.	648	30	19,440
Dec.	423	31	13,113
Jan.	688	31	21,328
Feb.	766	28	21,448
Mar.	1032	31	31,992
Apr.	1141	30	34,230
Season Total			177,170 BTU/Ft.^{2}
X Efficiency			X .25
Total collected over season			44,292.5 BTU/Ft.^{2}

The procedure is the same for hot water systems, except that you need to use the figures for every month of the year and a 45^0 collector tilt angle. Pool heating systems are done using a 30^0 tilt angle and the months of pool use (probably April through October). Remember also that the efficiencies are different. Go on to frame 8.

8. Now you can make an estimate of the total heat collected per square foot of collector over the heating season. To estimate the required collector size in square feet, you divide the estimate of heat collected per square foot into the total heat required.

You learned to estimate space heat requirements in module 3. Water heat requirements can be estimated by using the technique you learned to compute stored heat in Module 1.

Estimates of pool heating requirements are difficult to make due to heat loss from evaporation. The best way to make them is by analysis of pool heating bills in your area. We'll show you how to do that in module 6.

Suppose you live in a house in Corvallis. You've computed the solar heat collected per square foot of collector over the heating season, and got the result of frame 7 — 44,292.5 BTU/Ft.^{2}.

The heat loss multiplier for the entire house is 500 BTU/Hr.-^{o}F. and the degree-day totals for the heating season in Corvallis are listed below:

Oct.	366 ^{o}F.-Day
Nov.	580 ^{o}F.-Day
Dec.	729 ^{o}F.-Day
Jan.	766 ^{o}F.-Day
Feb.	597 ^{o}F.-Day
Mar.	574 ^{o}F.-Day
Apr.	456 ^{o}F.-Day

Find the total heat required and the size of collector required to produce 75% of that heat. Check your answers in frame 9.

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9. The total number of degree-days in the heating season is 4068 ^{o}F.-Day. The total amount of heat required is

$$Q = (24 \text{ Hr./Day}) (H) (\text{degree-days})$$

from module 3.

$$Q = (24 \text{ Hr./Day}) (500 \text{ BTU/Hr.-}^{o}\text{F.}) (4068 \text{ }^{o}\text{F.-Day})$$

$$Q = 48{,}816{,}000 \text{ BTU.}$$

75% of the total heat is

$$.75 \; Q = 36{,}612{,}000 \text{ BTU}$$

The required collector area A is

$$A = \frac{36{,}612{,}000 \text{ BTU}}{44{,}292.5 \text{ BTU/Ft.}^2}$$

$$A = 826.6 \text{ Ft.}^2$$

You can see that the collector area would have to be quite large to provide an average of 75% of the solar heat required over the heating season.

You could reduce the required size by increasing the collector efficiency, reducing the heat loss multiplier of the house with better insulation, or reducing the desired percent solar heating below 75%.

Using the monthly solar radiation totals obtained in frame 7, and a heat collecting efficiency of 25%, find the amount of solar heat collected by the 826.6 Ft.^{2} collector in each month. Compare it with the amount required in each month by using the degree-day information and the house heat loss multiplier from frame 8 to compute the required heat for each month. Then compute the percent solar heat for each month. You'll need the following formulas:

(1) $Q_C = EAQ_S$.

Q_C is the solar heat collected.

E is the <u>decimal</u> (%/100) efficiency of the system.

A is the area of the collector.

Q_S is the total solar radiation falling on a square foot of the collector for the period.

(2) percent solar = $100 \dfrac{Q_C}{Q_L}$

Q_C is the total solar heat collected from formula (1).

Q_L is the total heat lost from the house.

$Q_L = (24 \text{ Hr./Day}) (H) (\text{degree-days})$

Check your answers in frame 10.

Here are a few tables to help you with the computations:

Month	Q_S (BTU/Ft.^{2})	$Q_C = EAQ_S$ (BTU)
Oct.	35,619	
Nov.	19,440	
Dec.	13,113	
Jan.	21,328	
Feb.	21,448	
Mar.	31,992	
Apr.	34,230	

Month	Degree-Days (^{o}F.-Day)	Q_L = (24 Hr./Day) (H) (degree-days) (BTU)
Oct.	366	
Nov.	580	
Dec.	729	
Jan.	766	
Feb.	597	
Mar.	574	
Apr.	456	

Month	Q_C(BTU)	Q_L (BTU)	% Solar = $100 \frac{Q_C}{Q_L}$
Oct.			
Nov.			
Dec.			
Jan.			
Feb.			
Mar.			
Apr.			

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10. Your tables should have come out like the ones on the next page:

Month	Q_S (BTU/Ft.^{2})	$Q_C = EAQ_S$ (BTU)
Oct.	35,619	7,360,666
Nov.	19,440	4,017,276
Dec.	13,113	2,709,802
Jan.	21,328	4,407,431
Feb.	21,448	4,432,229
Mar.	31,992	6,611,147
Apr.	34,230	7,073,630

Month	Degree-Days (^oF.-Day)	Q_L = (24 Hr./Day) (H) (degree-days)(BTU)
Oct.	366	4,392,000
Nov.	580	6,960,000
Dec.	729	8,748,000
Jan.	766	9,192,000
Feb.	597	7,164,000
Mar.	574	6,888,000
Apr.	456	5,472,000

Month	Q_C (BTU)	Q_L (BTU)	% solar = $100 \frac{Q_C}{Q_L}$
Oct.	7,360,666	4,392,000	168
Nov.	4,017,276	6,960,000	58
Dec.	2,709,802	8,748,000	31
Jan.	4,407,431	9,192,000	48
Feb.	4,432,229	7,164,000	62
Mar.	6,611,147	6,888,000	96
Apr.	7,073,630	5,472,000	129

If you had trouble filling in the table, look over the computation for October, which we've outlined below:

$Q_C = EAQ_S$

Q_C = (.25) (826.6 Ft.^{2}) (35,619 BTU/Ft.^{2})

Q_C = 7,360,666 BTU

Q_L = (24 Hr./Day) (H) (degree-days)

Q_L = (24 Hr./Day) (500 BTU/Hr.-^oF) (366 ^oF.-Day)

Q_L = 4,392,000 BTU

$$\% \text{ solar} = 100 \frac{Q_C}{Q_L}$$

$$\% \text{ solar} = \frac{100(7,360,666)}{4,392,000}$$

% solar = 168 (approximately)

Don't go on until you can fill in the rest of the table, and your answers match ours.

You can see from the table that there's <u>no month</u> in which the system delivers exactly 75% of the required heat. For the collector to collect 75% of the heat required in December, we would have to make it 2-1/2 times as large as we did. It then would produce more heat than we need in every other month.

That's the main problem with solar space heating systems. When you need the most heat you get the least sunlight. Computing collector size by comparing total sunlight and total heat required for the entire season helps average things out. Go to frame 11.

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11. What three things could we have done to reduce the collector size required in frame 9? Check your answers in frame 12.

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12. We could have reduced the house heat loss, increased the system efficiency, or reduced the percentage of heat supplied by the sun.

Increasing system efficiency is probably the most expensive way to decrease collector size. Reducing the percentage of solar heat doesn't cost anything, but will increase the cost of fuel or electricity for the backup heating system. Reducing the heat loss from the house is usually the most economical way to reduce the required collector size.
Go to frame 13.

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13. Choosing the size of the heat storage container is not difficult if you know the percent solar heat for each month of the heating season. You just find the month in which the sun provides the largest percentage of the heat required that's still less than 75%. Then find the typical number of cloudy days per clear day in that month. The storage container should store at least as much heat as required for that many days in that month.

The number of cloudy days per clear day in a month is given by

$$\frac{N_T - N_C}{N_C} = \frac{100 - PPS}{PPS}$$

$\frac{N_T - N_C}{N_C}$ is the symbol we used for the number of cloudy days per clear day in module 4. PPS stands for percent possible sunshine. Percent possible sunshine can be found in weather data referenced in the introduction or by using

Percent possible sunshine = $153.8 \frac{H_{AV}}{H_o'} - 46.2$ with H_{AV} and H_o' the average and clear day horizontal solar radiation intensities. You may remember those formulas from module 4.

Here are percent possible sunshine figures for Corvallis for the months of the heating season.

Month	Percent Possible Sunshine
Oct.	50
Nov.	28
Dec.	17
Jan.	34
Feb.	26
Mar.	42
Apr.	46

Find the number of days of heat storage required for the solar heating system described in frames 3 through 10. Check your answer in frame 14.

14. You should have picked February as the month closest to, but below, 75% solar heat. You then should have used

$$\frac{N_T - N_C}{N_C} = \frac{100-PPS}{PPS}$$

$$\frac{N_T - N_C}{N_C} = \frac{100-26}{26}$$

$$\frac{N_T - N_C}{N_C} = \frac{74}{26}, \text{ or about 3 days}$$

The amount of heat you'll need to store is for 3 days in February. That's 3/28 of the total amount of heat required in February. How many BTU will you need to store? Refer to frames 9 and 10, and check your answer in frame 15.

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15. The total heat required for February is 7,164,000 BTU from frame 10. The heat storage required is 3/28 of that or 767,571 BTU.

Suppose you were going to use an air solar collector system with a rock bin for heat storage. C_p, the specific heat of the rocks is .2 BTU/Lb.-^oF., and their density ρ, including air spaces, is 60 Lb./Ft.^{3}. You're going to let the rock bin temperature vary between 80 ^oF. and 140 ^oF. Compute the required volume of the rock bin.

Use the formula

$$V = \frac{Q}{\rho C_p \Delta T}$$

from module 1. Check your answer in frame 16.

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16. $V = \frac{Q}{\rho C_p \Delta T}$

$$V = \frac{767{,}571\ \text{BTU}}{(60\ \text{Lb./Ft.}^3)\ (.2\ \text{BTU/Lb.-}^{o}\text{F.})\ (60\ ^{o}\text{F.})}$$

$$V = \frac{767{,}571\ \text{BTU}}{720\ \text{BTU/Ft.}^3}$$

$$V = \frac{767{,}571\ \text{BTU}\ (\text{Ft.}^3/\text{BTU})}{720}$$

$$V = 1066\ \text{Ft.}^3$$

That size rock bin would fit comfortably in the basement of a house or under its foundation.

Go to frame 17.

17. Sizing the collector of a solar hot water heating system is a bit easier than sizing the collector and storage system for a solar space heating system. The amount c. heat storage needed is set by the daily hot water use. One hundred gallons is adequate for an average family of four. Sixty gallons is enough if the family practices water conservation.

The amount of heat stored in the heated water can be computed easily using the formula you learned in module 1.

$$Q = \rho V C_p \Delta T$$

For ΔT you use the difference between the desired hot water temperature and the cold water inlet temperature. ρ is 8.34 Lb./Gal., and C_p is 1 BTU/Lb.-^{o}F.

Suppose your family uses 75 gallons of hot water a day. The hot water temperature is 120 ^{o}F. and cold water enters the storage tank at a temperature of 50 ^{o}F. How much heat do you need each day to heat your hot water? Check your answer in frame 18.

18. You use $Q = \rho V C_p \Delta T$

$V = 75$ Gal., $\rho = 8.34$ Lb./Gal, and $\Delta T = 70\ ^oF$.

$Q = (8.34$ Lb./Gal.) (75 Gal.) (1 BTU/Lb.-^oF.) (70 ^oF.)

$Q = 43{,}785$ BTU

That's all there is to finding the daily hot water heat requirement for a house. Go on to frame 19.

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19. The easiest way to choose a collector size for a solar hot water heating system is to match the solar energy collected on an average day with the daily amount of heat required. Using daily averages taken over the entire year rather than yearly totals lets you work with much smaller numbers and gives the same results. Find the average solar intensity in BTU/Ft.^{2}-Day over the entire year on a 45^o tilted collector in Corvallis. Use the table given below:

Month	Average Intensity (BTU/Ft.^{2}-Day)
Jan.	658
Feb.	760
Mar.	1070
Apr.	1251
May	1564
Jun.	1644
Jul.	1840
Aug.	1709
Sep.	1614
Oct.	1143
Nov.	626
Dec.	409

Check your answer in frame 20.

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20. There are three ways you could have computed the average solar intensity. You could have multiplied the daily average for each month by the number of days in the month, added the results, and divided the total by the total number of days in the year. Using 28.25 as the number of days in February (leap year every 4 years) and 365.25 as the number of days in the year, you get an average intensity of 1192.9 BTU/Ft.^{2}-Day over the entire year. Forgetting leap year changes the answer to 1193.2 BTU/Ft.^{2}-Day.

The other way to compute the average is to add the monthly totals and divide by 12. That way neglects the differences in the lengths of months. It gives an answer of 1190.7 BTU/Ft.^{2}-Day. All three methods give answers within .2% of each other. The last way is by far the quickest and causes only a small error. You can even use it to take averages over shorter periods than a year with very little error.

Go to frame 21.

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21. You can estimate the average amount of solar heat collected per square foot of collector by multiplying the average intensity by the estimated decimal (%/100) efficiency of the system. The formula is $q_c = EI$. The q_c stands for heat collected per square foot.

Solar water heating systems average about 50% efficiency over a year. Estimate the average amount of solar heat collected per square foot by a 45^o tilted collector in a solar hot water system in Corvallis. Check your answer in frame 22.

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22. You use $q_c = EI$. The decimal efficiency, E, is 50/100 = .5. The average intensity, I, is 1190 BTU/Ft.^{2}-Day. (You could have used a solar intensity of 1191 or 1193 BTU/Ft.^{2}-Day. If you did, your answer will be slightly higher.)

q_c = (.5) (1190 BTU/Ft.^{2}-Day) = 595 BTU/Ft.^{2}-Day.

The average amount of heat collected per square foot is then 595 BTU/Ft.^{2}-Day. Go to frame 23.

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23. To find the collector area required to heat the hot water, divide the desired amount of heat by the estimate of the average heat collected per square foot. The formula is

$$A = \frac{Q}{q_c}$$

Q is the symbol for the desired amount of heat.

A is the symbol for the collector area.

Find the collector area required to supply 75% of the daily hot water heat you computed in frame 17. Assume that q_c is the same as that computed in frame 22. Check your answer in frame 24.

24. You use $A = \frac{Q}{q_c}$ with Q equal to 75% of 43,785 BTU, or 32,838.75 BTU.

$$A = \frac{32{,}838.75 \text{ BTU/Day}}{595 \text{ BTU/Ft.}^2\text{-Day}}$$

$$A = 55.2 \text{ BTU/Day (Ft.}^2\text{-Day/BTU)}$$

$$A = 55.2 \text{ Ft.}^2$$

Go on to frame 25.

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25. You can also compute the percentage of the hot water heat supplied by solar energy in each month. The amount of heat collected on an average day of any month can be estimated using the formula $Q_c = q_cA = EIA$ since since $q_c = EI$. Q_c is the symbol for the estimated amount of heat collected on an average day by the entire collector. q_c is the symbol for the estimated amount of heat collected per square foot on an average day. E is the symbol for the estimated solar system efficiency. I is the symbol for the average intensity on the collector during the month in question. A is the symbol for the collector area.

Compute Q_c for each month of the year for the solar collector described in frames 19 through 24. Here's a table to help you compute:

Month	I (BTU/Ft.^{2}-Day)	q_c = EI(BTU/Ft.^{2}-Day)	Q_c = Aq_c(BTU/Day)
Jan.	658		
Feb.	760		
Mar.	1070		
Apr.	1251		
May	1564		
June	1644		
July	1840		
Aug.	1709		
Sep.	1614		
Oct.	1143		
Nov.	626		
Dec.	409		

Check your answers in frame 26.

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26. Your table should look like the one below.

Month	I(BTU/Ft.^{2}-Day)	q_c = EI(BTU/Ft.^{2}-Day)	Q_C = Aq_c(BTU/Day)
Jan.	658	329	18,161
Feb.	760	380	20,976
Mar.	1070	535	29,532
Apr.	1251	625.5	34,583
May	1564	782	43,166
Jun.	1644	822	45,374
Jul.	1840	920	50,784
Aug.	1709	854.5	47,168
Sep.	1614	807	44,546
Oct.	1143	571.5	31,547
Nov.	626	313	17,278
Dec.	409	204.5	11,288

You can now compute the percentage of the required heat supplied by solar energy in each month by dividing the total heat collected by the total heat required. Remember to use the total heat required — not 75% of it as you did when you estimated the collector size. The total heat required is the same for all months, because the weather doesn't affect hot water use very much.

The formula is % solar = $100 \frac{Q_C}{Q_L}$

Q_L is the symbol for the total hot water heat load.

Find the % solar for each month of the year for the solar hot water system described in frames 17 through 25. Check your answers in frame 27.

27. We hope you made a table like the one in the last frame:

Month	Q_C(BTU/Day)	Q_L(BTU/Day)	% solar = $100(\frac{Q_C}{Q_L})$
Jan.	18,161	43,785	41
Feb.	20,976	43,785	48
Mar.	29,532	43,785	67
Apr.	34,583	43,785	79
May	43,166	43,785	99
June	45,374	43,785	104
July	50,784	43,785	116
Aug.	47,168	43,785	108
Sep.	44,546	43,785	102
Oct.	31,547	43,785	72
Nov.	17,278	43,785	39
Dec.	11,288	43,785	26

You can see that the collector would have to be about three times as large to provide 75% of the required heat in December. If it were made that large, it would provide 3-1/2 times as much heat as required in July. To get all the required heat on an average December day would require 4 times as much area. On a cloudy day even that area wouldn't be enough.

Storing enough hot water for 5 or 6 cloudy December days would require a large, expensive storage tank which wouldn't be used much the rest of the year. Making the collector four times as large would also be quite expensive. For those reasons, it's generally uneconomical to attempt to get more than 75% of your hot water heat from the sun. Go on to the review questions.

Review Questions

1. List the approximate efficiencies of the three main types of active solar heating systems.

2. Describe the main differences between active and passive solar heating systems.

3. You live in a house in Corvallis which has about 4100 degree-days in the heating season. The house has a heat loss multiplier of 800 BTU/Hr.°F. You plan to install a solar space heating system which you expect will have an overall efficiency of 25%. The total amount of solar heat striking a square foot of collector during the entire heating season is 180,000 BTU/Ft.^{2}. Compute the collector size necessary to provide 50% of the heat required by the house during the heating season.

4. Suppose you've decided to build a 2000 Ft.^{2} collector for the house in question 3. In December you expect an average solar intensity of 450 BTU/Ft.^{2}-Day on the collector. The number of degree-days in December is 775. Compute the percent solar heat provided by the collector in December.

5. Suppose the collector in question 4 provides nearly 50% of the heat required in February by the house in question 3. The number of degree-days in February is 560. The percent sunshine in February is 25%. Compute the amount of heat storage required for the solar system.

6. Suppose you've decided to use a rock bin to store heat for a solar space heating system. You want to store 1,500,000 BTU. The specific heat of the rocks is 0.2 BTU/Lb.-^{o}F., and their density, including air spaces, is 75 Lb./Ft.^{3}. You intend to let the storage temperature vary 50^{o}F. Compute the volume of rock required.

Answers to Review Questions

1. Space heating: 25 to 30%
   Hot water heating: 50%
   Swimming pool heating: 60 to 70%
2. Active systems use forced convective heat transfer to move heat from collector to storage to heated space. They have pumps or fans to do it. The collector, storage, and heated space are generally separate, and thermally insulated from each other. Passive systems use free convection or radiation, or both, to move heat from collector to storage to heated space. Collector, storage, and heated space are often combined in one unit.
3. About 875 $Ft.^2$.
4. 23.4%
5. 1,152,000 BTU.
6. 2,000 $Ft.^3$.

If you had trouble with any of these questions, review frames 1 through 27 until you can do them all. Then go on to frame 28.

28. Estimating the size of the collector and heat storage container is the beginning of the design of a solar system. An important following step is estimating the size of the pump or fan which may be needed to move the heat transfer fluid. Both a pump and a fan may be needed if water and air are both used as heat transfer fluids. A system using free convective or radiative heat transfer (a passive system) may not need either a pump or a fan.

A pump or fan must have a capacity large enough to move heat at the maximum rate you estimate will be necessary. A pump or fan moving heat from a collector to storage should be able to move heat as fast as the collector can gather it, under the most favorable conditions. A pump or fan moving heat into a heated space should be able to do it as fast as required to keep the space warm on the coldest day anticipated.

The formula you used to compute the rate of fluid flow the pump or fan must produce is

$$\dot{V} = \frac{\dot{Q}}{C_v \Delta T}$$

$\dot{V}$ is the symbol for the rate of fluid flow.

$\dot{Q}$ is the symbol for the rate of heat flow.

C_v is the specific heat of the fluid per unit volume.

ΔT is the symbol for the temperature change the fluid experiences when the heat transfer takes place. You may remember the formula as the one for forced convective heat flow from module 2. Go to frame 29.

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29. To estimate the size of the pump or fan required to transfer heat from a collector, you need to estimate the collector's maximum rate of heat collection. The maximum rate of heat collection occurs when the collector is receiving maximum sunlight and the system is operating at maximum efficiency. Maximum system efficiency usually occurs during periods of maximum sunlight.

Periods of maximum sunlight occur at noon on clear days. The months in which they occur depend on the collector angle, which in turn depends on how the collector is being used. You can look up the maximum solar intensity for each month and collector angle in tables of clear day insolation in either of the recommended texts or the <u>ASHRAE Handbook of Fundamentals</u>.

During the heating season in Oregon, a collector tilted at a 60^o angle will receive maximum sunlight at noon on a clear day in February — 309 BTU/Ft.^{2}-Hr. A collector tilted at 45^o will receive maximum sunlight at noon on a clear day in March — 320 BTU/Ft.^{2}-Hr. A 30^o tilted collector will receive maximum sunlight at noon on a clear day in March or April — 317 BTU/Ft.^{2}-Hr. The maximum efficiency you should expect from the most expensive collectors under the best conditions is 80%.

To find the rate of heat collection you use a formula similar to the one used to find the total heat collected:

$\dot{Q}_c$ = EIA

$\dot{Q}_c$ is the symbol for the rate of heat collection.

E is the symbol for the decimal (%/100) collector efficiency.

I is the symbol for the solar radiation intensity on the collector.

A is the symbol for the collector area.

Suppose you have a 450 Ft.^{2} collector tilted at a 60^o angle. What's its maximum rate of heat collection under the best conditions?

Check your answer in frame 30.

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30. Using $\dot{Q}_c$ = EIA, with E = .8, I = 309 BTU/Ft.^{2}-Hr., and A = 450 Ft.^{2}, we get

$\dot{Q}_c$ = 111,240 BTU/Hr.

Suppose you're heating water with a 60 Ft.^{2} collector tilted at a 45^o angle. What's its maximum rate of heat collection? Check your answer in frame 31.

---

31. $\dot{Q}_c$ = 15,360 BTU/Hr.

To estimate the pump or fan size, you need an estimate of the temperature change that will occur in the fluid when it receives the heat from the collector. It shouldn't be more than 40 to 50 °F. or the collector will heat up too much, lose efficiency, and perhaps suffer damage from overheating.

Suppose you'll allow a 50 °F. temperature rise in the collector of frame 29. You'll use water as the heat transfer medium. [C_v = 8.34 BTU/Gal.-°F.] Use the formula for heat transfer fluid flow rate to find the necessary pump capacity in Gal./Hr. Check your answer in frame 32.

---

32. Using $\dot{V} = \frac{\dot{Q}}{C_v \Delta T}$, with $\dot{Q}$ = 112,240 BTU/Hr.,

ΔT = 50 °F., and C_v = 8.34 BTU/Gal.-°F., we find

$$\dot{V} = \frac{111,240 \text{ BTU/Hr.}}{8.34 \text{ BTU/Gal.-}\cancel{°F.})\ (50\ \cancel{°F.})}$$

$$\dot{V} = \frac{111,240 \text{ BTU/Hr. (Gal./BTU)}}{417}$$

$\dot{V}$ = 266.8 Gal./Hr.

Since most pump flow rates are given in Gal./Min., we should convert to Gal./Min. using the conversion factor Hr./60 Min. to change the /Hr. to /Min:

$\dot{V}$ = (Hr./60 Min.) 266.8 Gal./Hr.

$$\dot{V} = \frac{266.8 \text{ Gal./Min.}}{60}$$

$\dot{V}$ = 4.45 Gal./Min.

When you survey the sizes of pumps available, you'll find that the flow capacity of the required pump is relatively small.

The pump power required to move water at the rate you estimate will depend on how much pressure the pump must overcome to move the water. That will be determined by the height the water must be pumped to and the pressure losses due to pipe, valves, and fittings. Those can be calculated using tables in heating, refrigeration and air conditioning manuals or the ASHRAE Handbook of Fundamentals.

Suppose you'll allow a 40 ^{o}F. rise in the temperature of air (C_V = .018 BTU/Ft.^{3}-^{o}F.) pumped through the collector of frame 29. Compute the required fan capacity in Ft.^{3}/Hr. Check your answer in frame 33.

---

33. $\dot{V}$ = 154,500 Ft.^{3}/Hr.

Convert the fan capacity to Ft.^{3}/Min. Check your answer in frame 34.

34. $\dot{V}$ = 2575 Ft.^{3}/Min.

Required fan horsepower can also be computed using tables in heating, refrigeration, and air conditioning manuals or the ASHRAE Handbook. You can choose large duct sizes to keep the horsepower low. The height the air must be raised has only a slight effect on the fan horsepower. Duct lengths have an important effect, however. There will also be pressure drops in the heat storage bin which can be computed using information in the recommended texts. Go on to frame 35.

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35. Suppose you allow a water temperature rise of 40 $^{\circ}$F. in the small collector of frame 30. Compute the required pump capacity in Gal./Min. Check your answer in frame 36.

36. $\dot{V}$ = .77 Gal./Min.

If you didn't get our answer, review frames 28 through 35 and get help if you need it. When you can do the exercise, go on to frame 37.

---

37. There are two changes in procedure necessary to compute pump or fan sizes for space heating. The formula used is the same, but you use a different procedure to estimate the necessary heat flow rate.

You need an estimate of the maximum rate of heat loss, which will be the maximum required heat flow rate. The estimate of ΔT is also made differently. Go to frame 38.

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38. The maximum heat loss will occur when the outside temperature is lowest. You've learned to estimate the lowest outside temperature in module 3 using the mean of the annual extremes, and the 97-1/2% and the 99% temperatures. You also need to know the heat loss multiplier of the building.

The maximum rate of heat loss will be given by the formula

$\dot{Q}_L = H\Delta T$

$\dot{Q}_L$ = is the symbol for the estimated maximum rate of heat loss.

H is the symbol for the building's heat loss multiplier.

ΔT is the symbol for the temperature difference between the interior of the building and the outside air — 65 ^{o}F. minus the lowest outside temperature you anticipate.

You've designed a house with a heat loss multiplier of 600 BTU/Hr.-^{o}F. The design minimum outside temperature you've chosen is 15 ^{o}F. Estimate the house's maximum rate of heat loss in BTU/Hr. Check your result in frame 39.

39. $\dot{Q}_L = H\Delta T$

$\Delta T = 65\ ^oF. - 15\ ^oF. = 50\ ^oF.$

$\dot{Q}_L = (600\ BTU/Hr.-^oF.)\ (50\ ^oF.)$

$\dot{Q}_L = 30{,}000\ BTU/Hr.$

Another house has a heat loss multiplier of 700 BTU/Hr.-^{o}F. The design temperature is 10 ^{o}F. Estimate the maximum rate of heat loss. Check your answer in frame 40.

---

40. $\dot{Q}_L = 38{,}500\ BTU/Hr.$

To estimate ΔT in the formula for the required pump or fan capacity, you need to estimate the minimum temperature drop which will allow the fluid to transfer heat to the heated space efficiently. A good estimate for water, which requires a water to air heat exchange, is 25 ^{o}F. At water temperatures below 90 ^{o}F. it's difficult for heat to be transferred to 65 ^{o}F. air. Air at 80 ^{o}F. can be used to heat a 65 ^{o}F. room. A temperature difference of 15 ^{o}F. is all that's required.

Suppose you plan to heat the house of frame 38 with water. Estimate the maximum pump capacity required in Gal./Min. Check your answer in frame 41.

41. $\dot{V} = \frac{\dot{Q}}{C_v \Delta T}$

$\dot{Q} = \dot{Q}_L = 30{,}000$ BTU/Hr.

$C_v = 8.34$ BTU/Gal.-°F.

$\dot{V} = \frac{30{,}000 \text{ BTU/Hr.}}{(8.34 \text{ BTU/Gal.-}\cancel{°F.})\ (25\ \cancel{°F.})}$

$\dot{V} = \frac{30{,}000\ \cancel{\text{BTU}}\text{/Hr. (Gal./}\cancel{\text{BTU}}\text{)}}{208.5}$

$\dot{V} = 143.9$ Gal./Hr.

$\dot{V} =$ (Hr./60 Min.) (143.9 Gal./Hr.)

$\dot{V} = 2.4$ Gal./Min.

Suppose you were going to heat the same building with air. Estimate the required fan capacity in Ft.^3/Min.

Check your answer in frame 42.

42. $\dot{V} = \frac{\dot{Q}}{C_v \Delta T}$

$\dot{Q} = \dot{Q}_L = 30{,}000$ BTU/Hr.

$C_v = .018$ BTU/Ft.^{3}-^oF.

$\Delta T = 15\ ^oF$.

$\dot{V} = \frac{30{,}000 \text{ BTU/Hr.}}{(.018 \text{ BTU/Ft.}^3\text{-}^oF)\ (15\ ^oF.)}$

$\dot{V} = \frac{30{,}000 \text{ BTU/Hr. } (\text{Ft.}^3/\text{BTU})}{.27}$

$\dot{V} = 111{,}111$ Ft.^{3}/Hr.

$\dot{V} = 1851.9$ Ft.^{3}/Min.

Go on to frame 43.

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43. Estimate the required pump and fan sizes for the house of frame 39. Check your results in frame 44.

44. Pump: $\dot{V}$ = 3.08 Gal./Min.

$\dot{V}$ = 2376.5 $Ft.^3$/Min.

If you didn't get our answers, review frames 37 through 44 and get help if you need it. When you can do the exercise, go on to frame 45.

---

45. Preliminary estimates of the performance of passive solar systems can be made using the techniques you've studied in this module. The process is similar to estimating the performance of active solar space heating systems.

In passive systems solar heat is collected using south-facing glass surfaces which also serve as windows. Vertical glass is by far the most common, although some structures use glass inclined at angles which are close to the best winter collector angle.

Thermal storage is incorporated in the structure itself and is usually placed where it will receive direct sunlight in winter. The storage temperatures can't fluctuate as much as they can in active systems, because the temperature in the heated space tends to follow the storage temperature closely. You need a large thermal storage capacity to keep the building temperature from climbing too high on sunny days. Go to frame 46.

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46. There's no need to estimate the collection efficiencies of passive systems. You just compute the amount of solar heat which enters the structure through the south-facing glass, and compare the solar heat gain with the heat loss from the building. Only about 80% to 90% of the sunlight striking the glass enters the structure. The rest is lost to reflection and absorption in the glass. Multiplying the solar intensity on the glass by .8 is a safe method of computing the winter solar heat gain of the building.

The glass should be insulated at night and on cloudy days to prevent excess heat loss. Various insulating techniques using movable insulation are discussed in the two recommended texts. Go to frame 47.

---

47. Using removable insulation on the south-facing glass of a building changes the building's heat loss multiplier. When the insulation is in place, the heat loss multiplier is reduced. Your estimate of the building's heat loss should be corrected to take that fact into account. The easiest way

to do that is to compute an average heat loss multiplier for the glass and use it to compute an average heat loss multiplier for the building.

An average heat loss multiplier for the glass can be computed using the following formula:

$$H_G = \frac{H_{in}\ t_{in} + H_{unin}\ t_{unin}}{t_{in} + t_{unin}}$$

H_G stands for the average heat loss multiplier for the glass.

H_{in} stands for the heat loss multiplier of the insulated glass.

H_{unin} stands for the heat loss multiplier of the uninsulated glass.

t_{in} stands for the length of time the glass is uninsulated.

$t_{in} + t_{unin}$ is, of course, the total length of time over which heat is escaping through the glass.

The shortest way to compute the average heat loss multiplier is to estimate t_{in} and t_{unin} for an average day during the heating season. Eight hours is a fairly accurate estimate of t_{unin}.

During December and January — the peak of the heating season in Oregon — the glass is unlikely to be uninsulated for more than 8 hours a day. The rest of the time the sun won't be out and the glass will be covered by insulation. During the other months of the heating season, the glass will probably be uncovered longer each day, but the outside temperature will be high enough to keep daytime heat losses small.

Using an estimate of 8 hours a day for t_{unin} and an estimate of 16 hours a day for t_{in}, the formula for H_G becomes

$$H_G = \frac{8\ H_{unin} + 16\ H_{in}}{24}$$

It's difficult to make insulating covers for glass that give an H_{in} that is less than 1/10 of H_{unin}. Sealing their edges against air leaks tends to be difficult, and air leaks increase H_{in}. Making thick insulating covers that move easily is also difficult.

Estimating H_{in} to be 1/10 of H_{unin} is the same as estimating that you can cut the heat loss to 1/10 of the uninsulated value during sunless periods by insulating the glass. Doing that allows you to substitute 1/10 H_{unin} into the formula for H_G in place of H_{in}. That changes the formula to

$$H_G = \frac{8\ H_{unin} + 16\ (1/10\ H_{unin})}{24}$$

$$H_G = \frac{8\ H_{unin} + 1.6\ H_{unin}}{24}$$

$$H_G = \frac{9.6\ H_{unin}}{24}$$

$$H_G = .4\ H_{unin}$$

Less effective insulating covers that reduce H_{in} to 1/4 the value of H_{unin} change the formula for H_G as follows:

$$H_G = \frac{8\ H_{unin} + 16\ (1/4\ H_{unin})}{24}$$

$$H_G = \frac{8\ H_{unin} + 4\ H_{unin}}{24}$$

$$H_G = \frac{12\ H_{unin}}{24}$$

$$H_G = .5\ H_{unin}$$

The difference in heat loss multiplier between the most effective (and expensive) insulating covers and the least effective is only .1 H_{unin}.

It's now easy to estimate heat loss through glass that's insulated during sunless periods. Just cut H_G, the heat loss multiplier of the uninsulated glass, in half after computing it in the normal way. Be sure not to do that to the heat loss multiplier for any glass that won't be insulated at night or during cloudy weather. Go to frame 48.

---

48. Now we can outline the complete method for estimating the performance of a passive solar building:

   1. Compute the solar intensity on the south-facing glass surface during each month of the heating season. Remember to use <u>vertical</u> insolation numbers if the glass is vertical.
   2. Find the total solar radiation on one square foot of the glass for the entire heating season just as you do when estimating collector size.

3. Multiply by .8 to account for losses due to reflection and absorption in the glass. Then multiply by the area of the glass. You now have the total solar heat gained by the building over the heating season.
4. Compute the building heat loss multiplier as you learned in module 3, but cut H_G in half for the insulated south-facing glass.
5. Compute the total heat required for the heating season using the heat loss multiplier and degree-day information as you do when estimating collector size.
6. The result of step 3, the solar heat gain, divided by the result of step 5, the total heat requirement, is the fraction of the heating requirement provided by the sun. The percentage of solar heat is the fraction multiplied by 100. Go on to frame 49.

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49. You can see that the method for estimating the performance of a passive solar building is quite similar to the method for estimating collector size. The most time-consuming steps are estimating the monthly solar intensities, and computing the building heat loss multiplier. The solar intensities, once computed, can be used many times over. The building heat loss multiplier can be estimated roughly at first and computed more exactly when the final design of the building is complete.

The method is very useful for examining trial designs for workability before settling on a final design and making more exact computations.

List the steps of the method in your own words and check your answers in frame 50.

50. The steps are:

1. Estimate the monthly solar intensity on the building's south-facing glass for each month of the heating season.
2. Compute the total solar radiation hitting one square foot of the glass over the entire season.
3. Multiply by .8 to account for losses in the glass. Then multiply by the area of the glass.
4. Compute the building heat loss multiplier, halving the heat loss multiplier for the south-facing glass if it's to be insulated during sunless days.
5. Compute the total heat requirement for the heating season.
6. Divide the result of step 3 by the result of step 5 to find the fraction of the heat requirement supplied by the sun. The percentage of solar heat is the fraction multiplied by 100.

Review the steps until they're clear in your mind. Then go on to frame 51.

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51. Below is a table of solar radiation intensities on vertical surfaces for the heating season in Corvallis. Find the total solar heat gain over the heating season for a Corvallis house with 300 $Ft.^2$ of vertical south-facing glass.

Check your answer in frame 52.

Month	Solar Intensity on a Vertical Surface ($BTU/Ft.^2$)
Oct.	980
Nov.	588
Dec.	388
Jan.	637
Feb.	662
Mar.	811
Apr.	787

52. Here's a table computing the total radiation on one square foot of the glass for the entire heating season:

Month	No. of Days	Intensity (BTU/Ft.^{2})	Total Radiation (BTU/Ft.^{2})
Oct.	31	980	30,380
Nov.	30	588	17,640
Dec.	31	388	12,028
Jan.	31	637	19,747
Feb.	28	662	18,536
Mar.	31	811	25,141
Apr.	30	787	23,610
		Total for season	147,082

A rough estimate of the heating season total per square foot can be made by averaging the monthly intensities together and multiplying by 210 — the approximate number of days in the period. Adding the monthly totals and multipl·ing by 30 does the same thing. (It just eliminates dividing by 7 to get the average, and then multiplying by it as part of the 210 days.) If you do that you get 145,590 BTU/Ft.^{2}, slightly less than the answer above. A disadvantage of that technique is that you don't get the monthly totals which you can use to compute the fraction of solar heat for each month.

To compute Q_S, the total heat coming through the entire glass surface in a season, you multiply by .8 to allow for glass losses and then by the glass area.

Q_S = (.8) (147,082 BTU/~~Ft.~~^{2}) (300 ~~Ft.~~^{2})

Q_S = 35,299,680 BTU

Go to frame 53.

53. Find the total solar heat gain for December only for the Corvallis house of frames 51 and 52. Check your answer in frame 54.

---

54. The total solar radiation hitting each square foot of the glass in December is 12,028 BTU/Ft.^{2} from the table in frame 52. Multiplying by .8 and the area we find that Q_S for December is 2,886,720 BTU.

Go on to frame 55.

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55. Suppose the house in frame 51 has a heat loss multiplier of 400 BTU/Hr.-^oF., not including the south-facing glass. Uninsulated, the glass has a U value of 1.13 BTU/Hr.-Ft.^{2}-^oF. The glass will be insulated during sunless periods. Compute the total heat loss multiplier of the house.

Check your answer in frame 56.

---

56. H_G, the heat loss multiplier of the uninsulated glass is

H_G = UA

H_G = (1.13 BTU/Hr.-Ft.^{2}-^oF.) (300 Ft.^{2})

H_G = 339 BTU/Hr.-^oF.

Insulating the glass during sunless periods reduces H_G to half that value, so

H_G = 169.5 BTU/Hr.-^oF.

The total heat loss multiplier for the building is

$H = 400$ BTU/Hr.-^{o}F. + 169.5 BTU/Hr.-^{o}F.

$H = 569.5$ BTU/Hr.-^{o}F.

Go on to frame 57.

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57. There are about 4000 degree-days in the heating season in Corvallis. Compute the total heat required by the house in frames 51 through 56. Check your answer in frame 58.

---

58. The total heat requirement, or heat load, Q_L is given by

Q_L = (24 Hr./Day) (H) (Degree-Days)

Q_L = (24 Hr./Day) (569.5 BTU/Hr.-^{o}F.) (4000 ^{o}F.-Day)

Q_L = 54,672,000 BTU

Compute the percentage solar heat for the house of frames 51 through 57. Check your answer in frame 59.

59. Q_S = 35,299,680 BTU

Q_L = 54,672,000 BTU

The fraction of solar is Q_S/Q_L = .65

The percentage solar heat is 100 times .65 or 65%.

December in Corvallis has 729 degree-days. Compute the percent of solar heat for December for the house of frames 51 through 57. Check your answer in frame 60.

---

60. Q_S for December is 2,886,720 BTU from frames 53 and 54.

Q_L = (24 Hr./Day) (H) (Degree-days)

Q_L = (24 Hr./Day) (569,5 BTU/Hr.-^{o}F.) (729 ^{o}F.-Day)

Q_L = 9,963,972 BTU

The solar fraction of the heat is Q_S/Q_L = .29. The percentage solar is 100 times .29 or 29%. Just as in the collector size estimation, the percentage solar heat in the worst month is much less than it is for the entire heating season. Go on to frame 61.

---

61. Since heat storage in a passive solar building is inside the heated space, its temperature shouldn't normally be allowed to exceed 80 °F. or drop below 55 °F. The allowed ΔT for the storage is only about 25 °F. instead of the 60 to 100 °F. possible in active systems. That means a passive building will require about three or four times the heat storage volume required by a building with an active solar heating system.

Storage volume computations for passive systems are done in the same way as for active systems except for the difference in the allowed ΔT.

You calculate the amount of heat storage required for a typical number of consecutive cloudy days in the month that the system is 100% solar heated. Then you use the formula

$$V = \frac{Q}{C_v \Delta T} \text{ or } = \frac{Q}{C_p \Delta T}$$

to compute the required storage volume.

Suppose the house in frames 51 through 57 is 100% solar heated in March, which typically has 3 consecutive cloudy days. The number of degree-days in March is 574. Compute the total amount of stored heat required. Check your answer in frame 62.

62. The total heat required for March is

$$Q = (24 \text{ Hr./Day}) (H) (\text{degree-days})$$

$$Q = (24 \text{ Hr./Day}) (569.5 \text{ BTU/Hr.-}^{o}\text{F.}) (574\ ^{o}\text{F.-Day})$$

$$Q = 7{,}845{,}432 \text{ BTU}$$

For 3 days in March, you'll require 3/31 of that amount of heat. The required heat storage is then

$$Q = (3/31)\ 7{,}845{,}432 \text{ BTU}$$

$$Q = 759{,}235 \text{ BTU}$$

Suppose you're going to store the heat in a rock wall. The density of the rock is 200 Lb./Ft.^{3} and the specific heat of the rock per unit weight is 0.2 BTU/Lb.-^{o}F. You can only allow the rock's temperature to vary by 25 ^{o}F. How many cubic feet of rock will be needed to store the required heat for 3 days in March? Check your answer in frame 63.

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63. You need to use

$$V = \frac{Q}{\rho C_p \Delta T}$$

ρ = 200 Lb./Ft.^{3}; C_p = 0.2 BTU/Lb.-^{o}F.; ΔT = 25 ^{o}F.

$$Q = 759{,}235 \text{ BTU}$$

$$V = \frac{759{,}235 \text{ BTU}}{(200 \text{ Lb./Ft.}^3) (0.2 \text{ BTU/Lb.-}^o\text{F.}) (25\ ^o\text{F.})}$$

$$V = \frac{759{,}235 \text{ BTU}}{1000 \text{ BTU/Ft.}^3}$$

$$V = 759.235 \text{ BTU(Ft.}^3\text{/BTU)}$$

$$V = 759.235 \text{ Ft.}^3 \quad 759 \text{ Ft.}^3 \text{ (approximately)}$$

That volume corresponds to a foot-thick rock wall 8 feet high and almost 95 feet long.

How large a volume of water would be required to store the same amount of heat? Check your answer in frame 64.

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64. For water, the volume is

$$V = 3641 \text{ gallons}$$

or $V = 486.7 \text{ Ft.}^3$

You can use $V = \frac{Q}{C_v \Delta T}$ or $V = \frac{Q}{\rho C_p \Delta T}$

with Q and ΔT as before, $C_v = 8.34$ BTU/Gal.-^oF., $C_v = 62.4$ BTU/Ft.^{3}-^oF, or by using $C_p = 1$ BTU/Lb.-^oF. and the density of water = 3.34 Lb./Gal. or 62.4 Lb./Ft.^{3}.

You can see that a smaller volume of water than rock is required to store the heat.

Rock and concrete are still used often to store heat in passive solar buildings, because of their good structural properties and the problems associated with keeping large volumes of water in a heated living space. Go on to the review questions and post-test.

Review Questions

1. Your house has a heat loss multiplier of 700 BTU/Hr.-^{o}F. You plan to heat it to 65 ^{o}F. with air at a minimum temperature of 80 ^{o}F. The design temperature you've chosen is 10 ^{o}F. Compute the required Fan capacity in CFM (Ft.^{3}/Min.)

2. Suppose you're going to heat the house of question 1 with 90 ^{o}F water. Compute the necessary pump capacity in GPM (Gal/Min.)

3. You're building a passively solar heated house with 600 $ft.^2$ of vertical south-facing glass. The glass is a single thickness, but will be insulated at night. The uninsulated U-value of the glass is 1.13 BTU/Hr.-$Ft.^2$-^oF. The heat loss multiplier of the rest of the building is 300 BTU/Hr.-^oF. You expect the solar intensity on the glass to average 650 BTU/$Ft.^2$-Day in January, and January has 682 heating degree-days. Compute the percent solar heat provided in January by the south-facing glass.

4. Suppose you want to store 3 days of January heat for the house in Question 3. Compute the volume of water necessary to do it if you allow the storage temperature to fluctuate 20 ^oF.

Answers to Review Questions

1. 2377 $Ft.^3$/Min. (approximately).
2. 3.08 Gal./Min. (approximately).
3. 92.5%
4. 6068 Gal. or 8111 $Ft.^3$.

If you had trouble with any of the questions, go back through frames 28 through 64, and get help if you need it. When you feel ready, go on to the post-test.

Post-Test

1. Describe the main features of passive solar heating systems, and give an example of such a system.

2. Describe the main features of active solar heating systems, and give an example of such a system.

3. Describe the major differences between passive and active solar heating systems.

4. You own a house in Salem with a heat loss multiplier of 600 BTU/Hr.-^{o}F. You plan to install an active solar space heating system. Using the solar radiation and degree-day data below, compute the collector size necessary to provide 50% of the heat required during the heating season. Assume the overall efficiency of the solar heating system is 25%.

Month	Solar Intensity on Collector (BTU/Ft.^{2}-Day)	Degree-Days (^{o}F.-Day)
Oct.	1140	366
Nov.	648	580
Dec.	423	729
Jan.	688	766
Feb.	766	597
Mar.	1032	574
Apr.	1141	456

6. Compute the amount of heat storage necessary in the solar system for the house of question 4. Use the results of problem 5, and the percent possible sunshine data given below.

Month	Percent Possible Sunshine
Oct.	50
Nov.	28
Dec.	17
Jan.	34
Feb.	26
Mar.	42
Apr.	46

Compute the number of BTU needed first. Then assume you'll let the storage temperature fluctuate 80 ^{o}F., and store the heat in water. Compute the volume of water needed.

7. Now assume you want to heat the house of question 4 using a passive solar heating system. You'll replace the south wall with 500 $Ft.^2$ of vertical single pane glass. The U-value of the uninsulated glass will be 1.13 BTU/Hr.-$Ft.^2$-^oF. You'll insulate it at night and on very cloudy days. The heat loss multiplier of the rest of the structure will be 500 BTU/Hr.-^oF.-$Ft.^2$. Find the percent solar heat for each month of the heating season using the solar radiation and degree-day information below.

Month	Solar Intensity on Vertical Surface(BTU/$Ft.^2$-Day)	Degree-Days(^oF.-Day)
Oct.	980	366
Nov.	588	580
Dec.	388	729
Jan.	637	766
Feb.	662	597
Mar.	811	574
Apr.	787	456.

8. Suppose you've decided on a collector area of 600 $Ft.^2$ for an active solar space heating system. You're going to use an air collector, and allow the air temperature to rise a maximum of 50 ^oF. in the collector. You expect the maximum efficiency of the collector to be 80%, and the maximum solar intensity falling on it to be 310 BTU/$Ft.^2$-Hr. Compute the required fan capacity in CFM ($Ft.^3$/Min.)