LA-5967-MS
Informal Report

c.3

UC-2
Date Written: March 1975
Date Issued: May 1975

SOLAR HEATING HANDBOOK FOR LOS ALAMOS

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
CONTRACT W-7405-ENG. 36

The information developed in this report was presented at a Los Alamos energy seminar on February 26, 1975 and has been reproduced and distributed in the interest of disseminating solar heating system design information and assisting local residents in saving fuel.

ERRATA:

Page 36 - The word inload should be in load

Page 44 - Subscript c should appear after each ft^2 - (example: 5 BTU/°F/ft_c^2.)

Page 70 - Second column, 4th line - the word plastic should be plaster.

SOLAR HEATING HANDBOOK FOR LOS ALAMOS

by

D. Balcomb, J. C. Hedstrom,
S. W. Moore, and B. T. Rogers

Los Alamos Scientific Laboratory
Los Alamos, NM 87544

ABSTRACT

Performance calculations are presented for three types of active solar heating installations in a Los Alamos, New Mexico climate. The analyses are based on hour-by-hour computer simulations using actual input weather data for the period between September 1972 and August 1973, a relatively cold year. The effect of variations in important design parameters are given in graphical form. The systems studied are as follows: domestic hot water heating using liquid cooled collectors; space heating using liquid cooled collectors, water heat storage, and forced air distribution; and space heating using air cooled collectors, rock-bed heat storage, and forced air distribution. Sun-tempered or passive systems are discussed qualitatively. Design considerations, collector types, and collector coolants are discussed. Sources of information are listed including books, bibliographies, journals and associations.

CONTENTS

INTRODUCTION

The solar energy incident on the outside of a building can be used to provide a major fraction of the domestic hot water or space heating requirements of the building in most of the United States. A solar heating system generally consists of solar collectors to absorb the sun's heat energy and a heat storage medium to hold excess heat for release during periods when the sun does not shine. Since the weather and solar insolation pattern varies significantly from place to place it is desirable to base the design of a solar heating system on the local situation. The weather in northern New Mexico, with a cold climate and high incidence of sunshine, is particularly conducive to solar heating.

Solar insolation and weather data have been recorded at Los Alamos and translated to an hourly numerical listing for the one-year period from September 1972 to August 1973. The performance calculations presented in this report are based on these data and should be representative of performance during an unusually long heating season. Since the weather varies from year to year, one must expect some deviation in the overall performance from year to year.

Solar heating is a technology which is generallly considered to be available for general use. A growing number of companies are marketing components and whole systems. As fuel prices rise the extra cost associated with the installation of a solar heating system becomes more attractive. The growing market, mass production of components, and experience in installation of systems can be expected to bring costs down as solar heating becomes widespread.

Solar energy can also be used for cooling a building or for electrical power generation. These technologies are not yet considered to be economic and are not discussed in this handbook.

SOLAR ENERGY AVAILABILITY IN LOS ALAMOS

For the year analyzed, the total solar radiation incident on a flat surface tilted 45° and facing due south was 586,000 Btu/yr per sq. ft. The month-to-month variation is given in the table below. The day-to-day variation is shown on the graph.

Month	Btu/Mo/ft$^{2*}_{c}$	Degree days/mo
Sept., 1972	54010	229
Oct., 1972	40040	536
Nov., 1972	43720	1041
Dec., 1972	41620	1162
Jan., 1973	48690	1224
Feb., 1973	44780	998

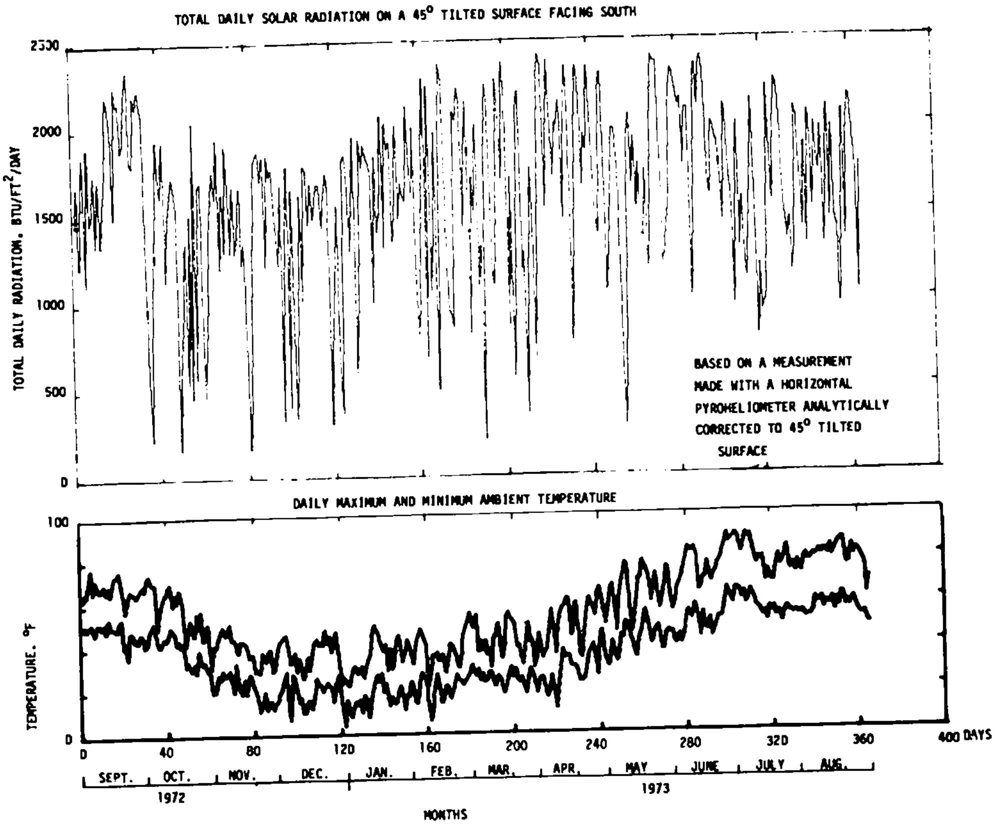
*Tilted at 45° facing due south.

OUTSIDE TEMPERATURE VARIATIONS IN LOS ALAMOS

For the year analyzed, the total space heating load was 18% greater than normal for Los Alamos: 7494 degree-days** versus a normal value of 6350 degree-days. The snowfall was significantly greater than normal—72 in. versus a normal value of 50 in. Los Alamos is located in mountainous terrain at an elevation of 7200 ft and a latitude of 35.8° N.

Month	Btu/Mo/ft$^{2*}_{c}$	Degree days/mo
Mar., 1973	47540	990
Apr., 1973	55870	762
May, 1973	50900	363
June, 1973	57960	115
July, 1973	47650	49
Aug., 1973	53100	25

** Base: 65°F.


TOTAL DAILY SOLAR RADIATION ON A 45° TILTED SURFACE FACING SOUTH
TOTAL DAILY RADIATION, BTU/FT²/DAY
2500
2000
1500
1000
500
0
BASED ON A MEASUREMENT MADE WITH A HORIZONTAL PYROHELIOMETER ANALYTICALLY CORRECTED TO 45° TILTED SURFACE
DAILY MAXIMUM AND MINIMUM AMBIENT TEMPERATURE
TEMPERATURE, °F
100
0
0
40
80
120
160
200
240
280
320
360
400 DAYS
SEPT.
OCT.
NOV.
DEC.
JAN.
FEB.
MAR.
APR.
MAY
JUNE
JULY
AUG.
1972
1973
MONTHS

TYPES OF SYSTEMS

Solar heating of swimming pools is particularly cost effective because relatively inexpensive collectors can be used. This is because glazing is not required at low temperatures typical of pool water. LASL has not made performance calculations, however manufacturers recommend a collector area of roughly one-half the pool area being heated. Pools should be covered at night to reduce evaporative and radiation cooling.

Domestic solar water heaters are attractive because they work year around and can usually be retrofit to existing dwellings because the total collector area requirements are small (50-200 ft^2). Tank type systems which do not require circulation have been designed. More commonly, circulation of collector coolant is achieved either with a pump or by placing the storage tank above the collector and utilizing natural circulation.

Many kinds of space heating systems have been devised. The more common types utilize a liquid or air to cool separate solar collectors, water or a rock bed for heat storage, and forced air, convectors, or radiant panels for heat distribution. Domestic water heating is frequently combined with space heating.

In sun-tempered or passive designs, one attempts to utilize the architecture of a building to maximize solar gains during the cold season, minimize heat losses, and provide thermal storage within the building.

TYPES OF SYSTEMS

- SWIMMING POOL HEATERS
  - UNGLAZED PLASTIC COLLECTORS
- DOMESTIC HOT WATER HEATERS
  - NON-CIRCULATING
  - OR
  - CIRCULATING
    - THERMOSIPHON
    - PUMPED
- SPACE HEATING (ACTIVE SYSTEMS)
  - LIQUID COOLED COLLECTORS / WATER STORAGE / FORCED AIR DISTRIBUTION OR CONVECTOR DISTRIBUTION
  - OR
  - AIR COOLED COLLECTORS / ROCK BED STORAGE / FORCED AIR DISTRIBUTION
  - USUALLY COMBINED WITH DOMESTIC HOT WATER HEATING
- SUN-TEMPERED BUILDING DESIGNS (PASSIVE SYSTEMS)

SOURCES OF INFORMATION

New Mexico Solar Energy Association

The New Mexico Solar Energy Association is a non-profit organization incorporated under the laws of the State of New Mexico. Article II of the Bylaws states: "The purposes of this Association shall be to further solar and related arts, sciences and technologies and concern for the ecologic, social and economic fabric of the region. This shall be accomplished through exchange of ideas and information by means of meetings, publications and information centers. The Association shall serve to inform public institutional and governmental bodies and seek to raise the level of public awareness of its purposes."

OFFICERS

Chairman - Keith W. Haggard, Santa Fe
Vice-Chairman - William Mingenbach, Taos
Secretary-Treasurer - Susan Yanda, Nambe

NMSEA membership is roughly 220 as of February 1975. The NMSEA will petition for local chapter status in the American Section of the International Solar Energy Society.

Some Current Programs

A collection of solar literature has been established at the Santa Fe City Library which is available to members in other areas through inter-library loans. A committee is working to establish a solar radiation monitoring network.

Proceedings of the two-day 1974 Association conference are being prepared for publication and can be pre-ordered for $5.00. Approximately 30 papers will be included. Also available from the Association is a reprint of Chapter 59, ASHRAE Handbook, 1974—Heating Solar Energy Utilization for Heating and Cooling (20 pgs)—$1.00 per copy. Newsletters will be issued periodically and occasional one day conferences will be sponsored in addition to the annual meeting.

CONSULTANTS

The NMSEA maintains a list of solar heating consultants in the New Mexico region.

NMSEA Address

602-1/2 Canyon Road
Santa Fe, New Mexico 87501

SOURCES OF INFORMATION

BOOKS

GENERAL: FARRINGTON DANIELS,
DIRECT USE OF THE SUN'S ENERGY - REPRINTED IN PAPERBACK

TECHNICAL: JOHN DUFFIE AND WILLIAM BECKMAN
SOLAR ENERGY THERMAL PROCESSES
WILEY-INTERSCIENCE

BIBLIOGRAPHIES

SOLAR THERMAL ENERGY UTILIZATION 1957-74
TECHNOLOGY APPLICATIONS CENTER
UNIVERSITY OF NEW MEXICO (1974)
TWO VOLUMES, $37.50

SOLAR ENERGY, A BIBLIOGRAPHY
U. S. ATOMIC ENERGY COMMISSION
TID-3351 (1974), $10.60

JOURNALS

SOLAR ENERGY (ISES JOURNAL)
ASHRAE JOURNAL

EQUIPMENT

THE MARCH 1975 ISSUE OF POPULAR SCIENCE CARRIES A LIST OF 33 MANUFACTURERS OF SOLAR ENERGY COMPONENTS AND SYSTEMS.

DIRECTORY

1974 SOLAR DIRECTORY - COMPILED AND DISTRIBUTED BY:
ENVIRONMENTAL ACTION OF COLORADO
UNIVERSITY OF COLORADO, DENVER
1100 14TH ST., DENVER, CO 80702

LISTS CONSULTANTS, MANUFACTURERS, DISTRIBUTORS, RESEARCHERS, PROJECTS, AND BIBLIOGRAPHY.

DESIGN CONSIDERATIONS

Solar energy is an area in which the individual can make a personal contribution to alleviation of the national energy problem without energy privation. However, the amateur is advised to be very well informed or to seek the services of a consultant before committing to a major investment.

The first consideration in the thermal design of the building should be to minimize the load within the constraints imposed by economics and architecture. Adequate insulation, double glazing, control of infiltration, and passive control of the solar gains are usually more cost effective than active solar heating. After the loads have been minimized by these techniques then active systems might be considered to satisfy the bulk of the remaining load.

The system should always be designed with a full-capacity auxiliary heating unit for periods of extended cloudiness.

Design optimization usually involves a tradeoff between cost and performance. At some point the extra performance which can be achieved by adding on more equipment or material will exceed the savings incurred. This is true at some point of extra insulation extra collector area, and many other design variables. In a few cases a true performance optimum exists, for example, collector tilt and orientation.

Component lifetime and maintenance should receive major consideration in the design. The solar energy which falls on a building may be free but the equipment involved can represent 5 to 15% of the building cost and must have a lifetime of 15 to 30 years to warrant the investment. Corrosion, infrared degradation, weathering, and fouling are areas which deserve special consideration.

SOLAR HEATING ECONOMICS IN LOS ALAMOS

BASICALLY
A
TRADEOFF: INSTALLATION COST OF SOLAR HEATING SYSTEM **VERSUS** FUTURE COST OF FUEL SAVED

FOR ONE FT$_c^2$ (160,000 BTU/YR)	THE COMPETITION		
	GAS (70% EFF.)	ELECTRIC	PROPANE (70% EFF.)
CURRENT ENERGY COST, $/10^6 BTU	$1.60	$7.62	4.64
$/YR	0.256	1.21	0.74
ASSUMED ESCALATION RATE	14%	7%	10%
20 YEAR TOTAL ENERGY COST	$23.30	$49.60	42.38
PRESENT VALUE (7% INTEREST)*	$10.00	$24.20	19.49
PRESENT VALUE (10% INTEREST)*	$ 7.34	$18.84	14.80

The conclusion is that one can afford to spend $7.34 to $10.00 per sq. ft. of collector for the total solar heating system in competition with gas heating or $18.84 to $24.20 in competition with electric heating. These figures are based on collecting and using 160,000 BTU/Ft$_c^2$/Year which is typical for a 75% solar heating system in Los Alamos.

Typical present system installation costs probably would fall within the range of these values.

---

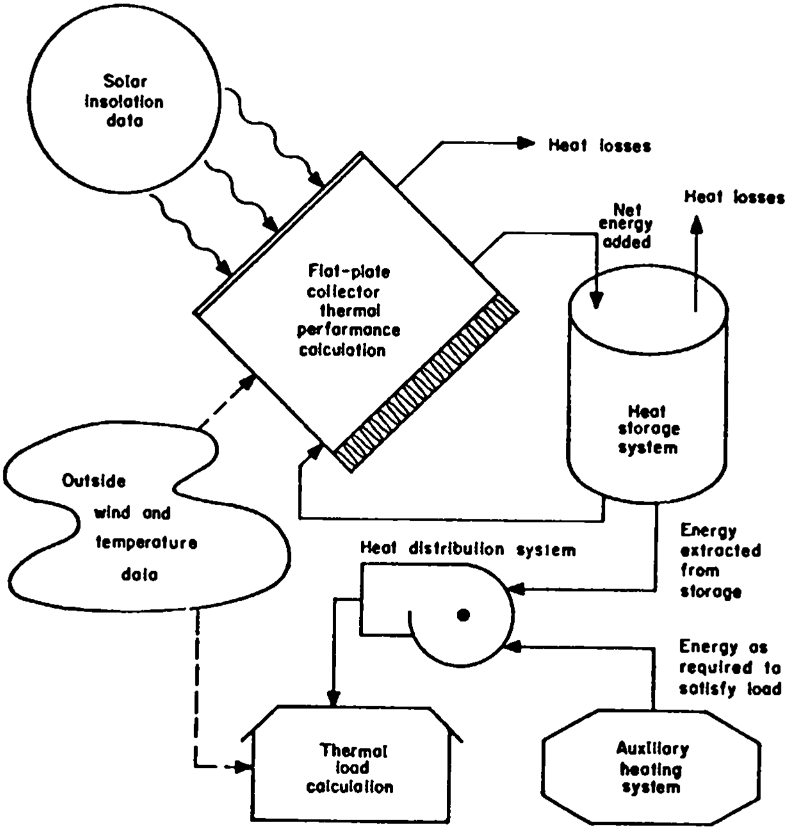
*The present value is that amount of money which, if invested at the given interest rate, will generate sufficient capital over the 20 year period to pay off the energy cost as it occurs.

SIMULATION ANALYSIS

Prediction of the performance of a solar heating system is based on a simulation analysis using the observed weather and solar data. The actual system is simulated by a digital computer code on an hour-by-hour basis. The simulation model is shown schematically.

At each hour the net energy which can be extracted from the collector is calculated. This is determined based on the solar insolation, the collector design, the outside temperature and wind condition, and the inlet fluid temperature from storage. If this energy is positive it is added to storage. The thermal load is calculated either from the outside temperature (for space heating) or a fixed schedule (for water heating). This energy is extracted from storage by the heat distribution system to satisfy the load. If the load cannot be totally satisfied from storage then auxiliary heat is added as required to make up the difference. The change in storage temperature over the hour is the net energy added from the collector minus storage heat losses minus the energy extracted by the thermal load divided by the storage heat capacity.

This calculation is repeated for each of the 8760 hours of the year. All energy flows are summed hour-by-hour and both monthly and yearly summaries are printed out. A typical year-long calculation requires only 58 seconds on the Los Alamos CDC 6600 computer and thus it is feasible to study the effect of changes in many design parameters.



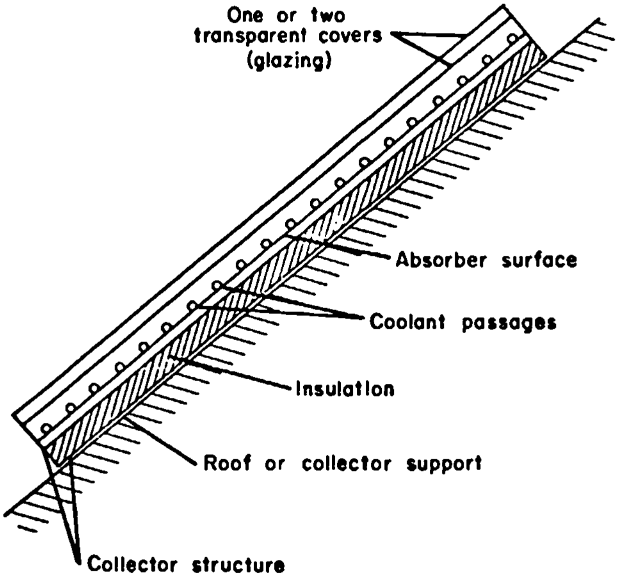
SIMULATION SCHEMATIC

FLAT PLATE COLLECTOR DESIGN

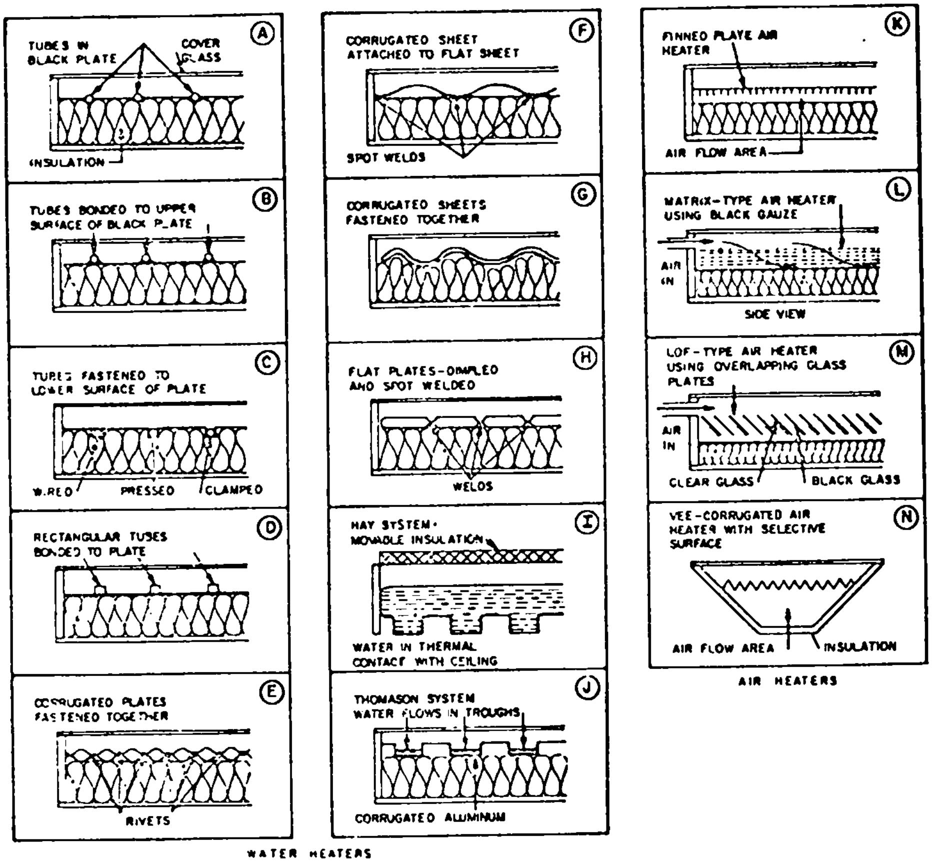
Many types of solar collectors have been designed and built. At the low temperatures used for water or space heating, flat plate types work with reasonable efficiency and are relatively easy to construct.

The major functional parts of a collector are the absorber surface, coolant passages, cover glazing, and back insulation.

Collectors are designed to maximize absorption of solar radiation and minimize heat losses. The predominant heat loss mechanisms from the front face are by convection and radiation. Convection losses are controlled by the use of one or more transparent covers. Radiation losses are sometimes reduced by means of a "selective" coating on the absorber surface which has a high absorptance for the solar spectrum and a low emittance for the infrared re-radiation spectrum. Other minor heat loss mechanisms are conduction to the collector backside and edge.



COLLECTOR TYPES



This potpourri of collector types is taken from Chapter 59 of the ASHRAE Handbook, 1974, "Solar Energy Utilization for Heating and Cooling," by John I. Yellott

COLLECTOR PERFORMANCE

Collector efficiency is defined as the ratio of the heat removed by the coolant divided by the incident solar energy. It is not a single number but is dependent on a variety of conditions such as the coolant temperature and flow rate, the angle of the incident sunlight, and wind velocity. It is also dependent on collector design parameters.

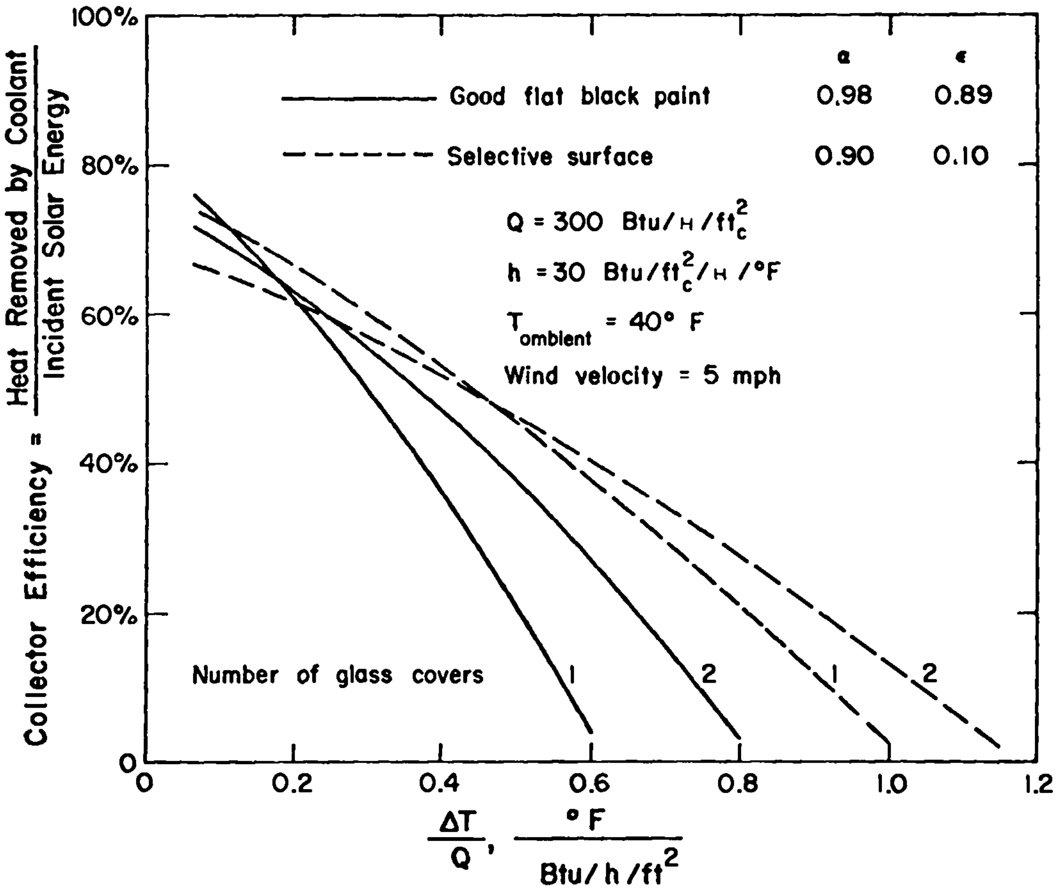
Collector performance is calculated by performing a detailed heat balance on the absorber surface and on each sheet of glazing, accounting for solar and infrared absorption and radiation, convection and conduction heat flows.

Collector efficiency is shown at the right for one set of conditions. It has become standard practice to plot collector efficiency as a function of the parameter $\Delta T/Q$.

$$\frac{\Delta T}{Q} = \frac{\text{Average Collector Coolant Temperature} - \text{Ambient Temperature}}{\text{Incident Solar Radiation}}, \quad \frac{{}^{\circ}F}{BTU/Ft^2/hr}$$

A thorough discussion of collector performance is given in Chapter 7 of "Solar Energy Thermal Processes", J. A. Duffie and W.A. Beckman, Wiley-Interscience, 1974.

FLAT-PLATE SOLAR COLLECTOR PERFORMANCE MAP



LIQUID COLLECTOR COOLANTS

The selection of a liquid collector coolant is a choice between conflicting requirements. One would desire a stable non-freezing, non-boiling, non-corroding, non-flammable, inexpensive, high specific heat, non-viscous, non-toxic, and non-energy-intensive fluid. Many liquids have been tried and all have been found deficient in some category. Ethylene glycol/water mixtures are often used. LASL is currently evaluating a number of fluids among which a class of light paraffinic oils such as Dowtherm HP or Thermia 33 show promise

The use of a collector coolant other than water implies that a heat exchanger is required between the collector coolant circuit and the water in the heat storage tank.

LIQUID COLLECTOR COOLANTS

	WATER	85% ETHYLENE GLYCOL/WATER	PARAFFINIC OIL	UCON (POLYGLYCOL) 50-HB-280-X
FREEZING POINT	32°F	-33°F	--	--
POUR POINT	--	--	10°F	-35°F
BOILING POINT (@ ATM. PRESS.)	212°F	265°F	700°F	600°F
CORROSION	(CORROSIVE TO Fe OR Al, REQUIRES INHIBITORS)		NON-CORROSIVE	NON-CORROSIVE
FLUID STABILITY	(REQUIRES pH OR INHIBITOR MONITORING)		GOOD[*]	GOOD[**]
FLASH POINT	NONE	NONE	455°F	500°F
SPECIFIC HEAT	1.	.65	.46	.46
BULK COST ($/GAL)	--	2.35	1.00	4.40
SYSTEM FLUID COST/FT^2 COLLECTOR	--	$.19	$.11	$.38

---

[*] REQUIRES AN ISOLATED COLD EXPANSION TANK OR NITROGEN CONTAINING HOT EXPANSION TANK TO PREVENT SLUDGE FORMATION.

[**] CONTAINS A SLUDGE FORMATION INHIBITOR.

DESIGN PARAMETERS OF THE LIQUID/WATER/FORCED AIR SYSTEM

Parameter	Nominal Value
Collector area ratio	0.5 $ft_c^2 ft_h^2$
Collector design:	
Number of glazings	1
Glass absorption	6% normal*
Glass reflection	8% incidence
Back insulation R	12°F hr ft_c^2/Btu
Coolant flow rate	20 Btu/°F/hr/ft_c^2
Solar absorptivity	0.98 (good flat-
IR emissivity	0.89 black paint)
Heat capacity	0.3 Btm/°F/ft_c^2
Heat transfer coeff.	30 Btu/°F/hr/ft_c^2
Tilt	45°
Orientation	due south

Parameter	Nominal Value
Storage:	
Mass heat capacity	15 Btu/°F/ft_c^2
Heat loss	(no net loss)
Distribution system	(forced air):**
Finned-tube coil	0.8 effectiveness
Air flow rate	1.64 cfm/ft_c^2
Design air	
Dist. Temp.	120°F
Building Load:	12 Btu/°F/day/ft_h^2 (68°F maintained)

---

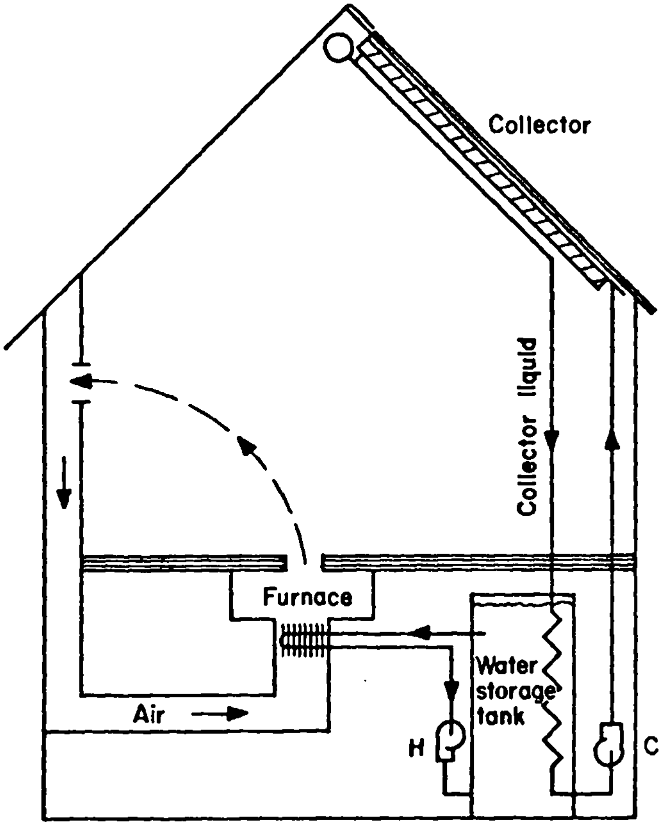
*These values apply for normal incidence on ordinary double strength glass (1/8"). For other angles of incidence the Fresnel equation is used.

**The coil and air circulation are sized to meet the building load with an outside temperature of −2°F with 133°F water and an air flow rate adequate to heat the space at an air temperature of 120°F.

SYSTEM SCHEMATIC

When the collector temperature exceeds the water tank storage temperature, Pump C is operated to transfer solar heat to storage.

When the building calls for heat, Pump H is operated to heat the air upstream of the furnace through a finned-tube coil. If the energy added is insufficient to maintain room temperature, the furnace is operated.

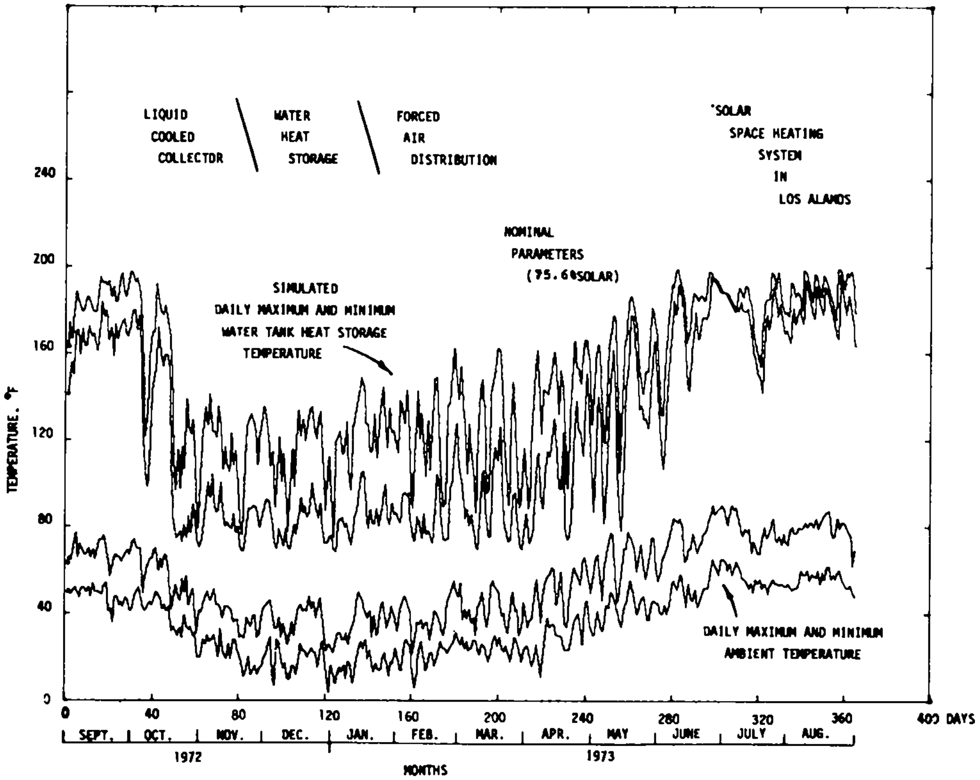


Liquid Cooled Collectors / Water Storage / Forced Air Distribution

LIQUID/WATER/AIR SOLAR SPACE HEATING SIMULATION RESULTS

The graph on the opposite page shows the calculated maximum and minimum storage temperature for each day of the year. Total energy flows for each month are as follows (for one ft^2 of collector):

Month (1972-73)	Building Load, Btu/month	Solar Heat Collected, Btu/month	Auxiliary Heat Used, Btu/month	Solar Heating, %
Sept.	7840	8460	0	100.
Oct.	15180	10750	2600	82.8
Nov.	27140	19450	8230	69.7
Dec.	30120	18530	11340	62.3
Jan.	31600	21810	9870	68.8
Feb.	25970	18920	7480	71.2
Mar.	26000	18260	7350	71.7
Apr.	20450	17500	3360	83.6
May	11240	11250	3510	96.9
June	5070	5590	0	100.
July	3510	3290	0	100.
Aug.	3060	3100	0	100.
Totals (Btu/yr)	207200	156900	50600	75.6

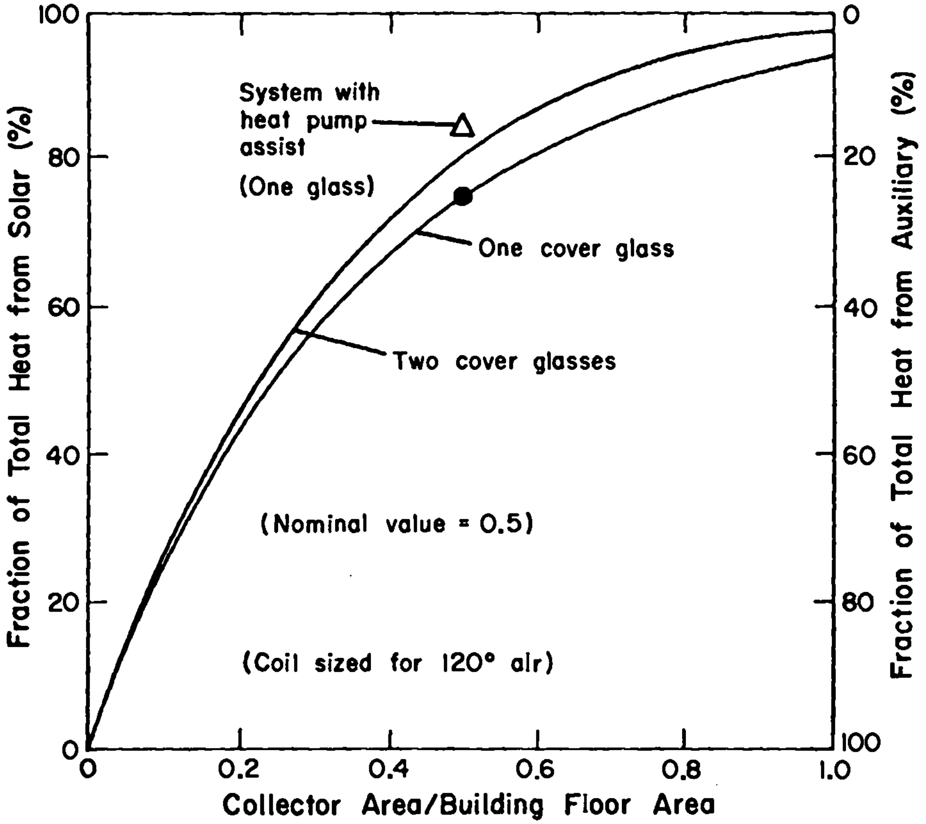

LIQUID COOLED COLLECTOR
WATER HEAT STORAGE
FORCED AIR DISTRIBUTION
SOLAR SPACE HEATING SYSTEM IN LOS ALAMOS
NOMINAL PARAMETERS (75.6%SOLAR)
SIMULATED DAILY MAXIMUM AND MINIMUM WATER TANK HEAT STORAGE TEMPERATURE
DAILY MAXIMUM AND MINIMUM AMBIENT TEMPERATURE
TEMPERATURE, °F
0
40
80
120
160
200
240
0
40
80
120
160
200
240
280
320
360
400 DAYS
SEPT.
OCT.
NOV.
DEC.
JAN.
FEB.
MAR.
APR.
MAY
JUNE
JULY
AUG.
1972
1973
MONTHS

This graph can be used to determine either the required collector array size to achieve a desired performance with a given load or the effect of changes in load with a given collector area. A nominal building load of 12 Btu/ft^2_{fl}/F/day was assumed. If the building load is different than this then the collector-to-building area ratio can be scaled proportionally.

The effect of double glazing is to reduce the collector heat losses. However, it also reduces the sunlight reaching the absorber surface and increases the collector cost.

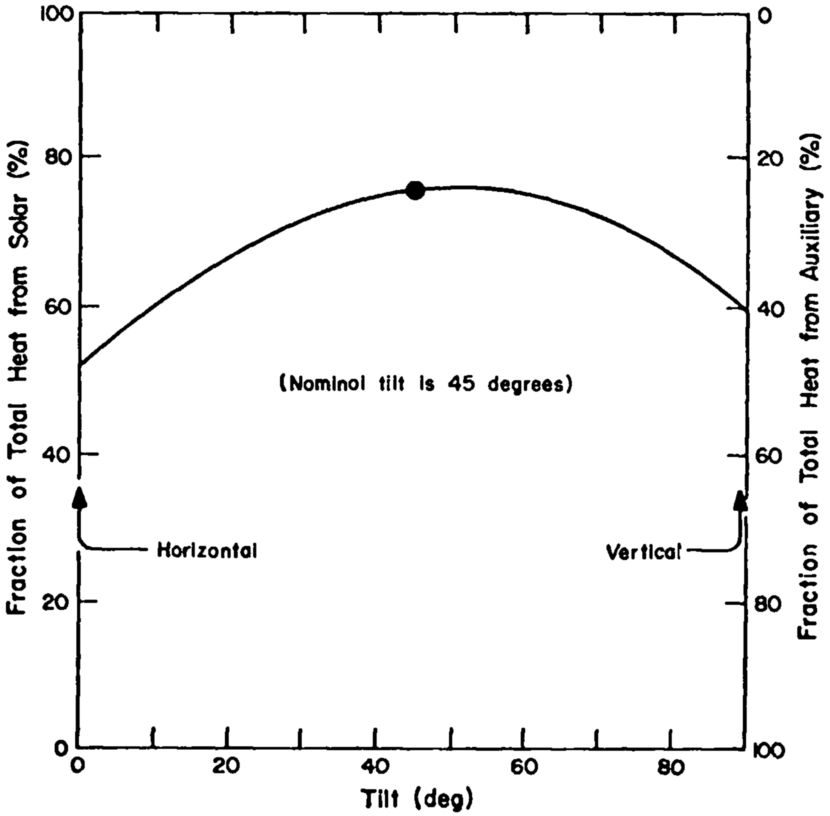
If a water-to-air heat pump is used as the auxiliary system in place of the furnace, then heat can be pumped out of storage into the space. This reduces the storage temperature and therefore increases the collector efficiency and overall system effectiveness. The one point shown indicates an overall increase in performance of 10%. This would be very appropriate in installations where a heat pump is required for summer cooling anyway and therefore the additional cost of the heat pump is minimal.

Liquid/Water/Forced Air System in Los Alamos
EFFECT OF COLLECTOR ARRAY SIZE



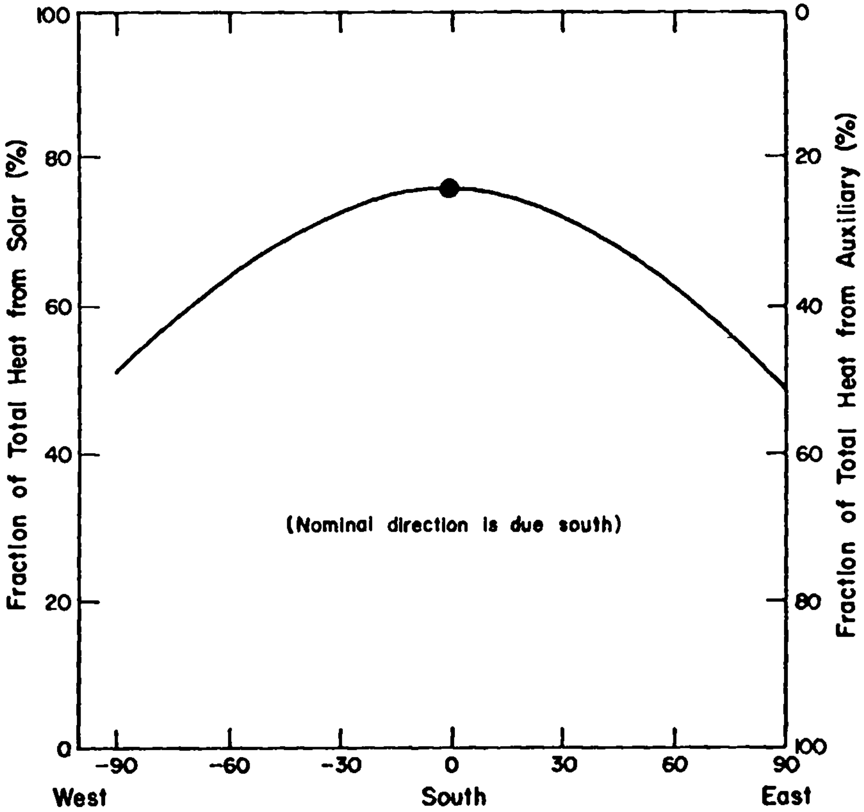
Collector tilt angle is an important design consideration. The optimum value is 50° corresponding closely to the oft-quoted rule-of-thumb of latitude plus 15°. The performance is within 2% of maximum over the range of 38 to 65°, within 5% of maximum over the range of 29 to 73°, and within 10% of maximum over the range of 19 to 82°.

Liquid/Water/Forced Air System in Los Alamos
EFFECT OF COLLECTOR TILT



Collector orientation is also important. As expected, a due south orientation is optimum; however, variations of 30° east or west only reduces performance about 3%.

Liquid/Water/Forced Air System in Los Alamos
EFFECT OF COLLECTOR ORIENTATION (45° TILT)



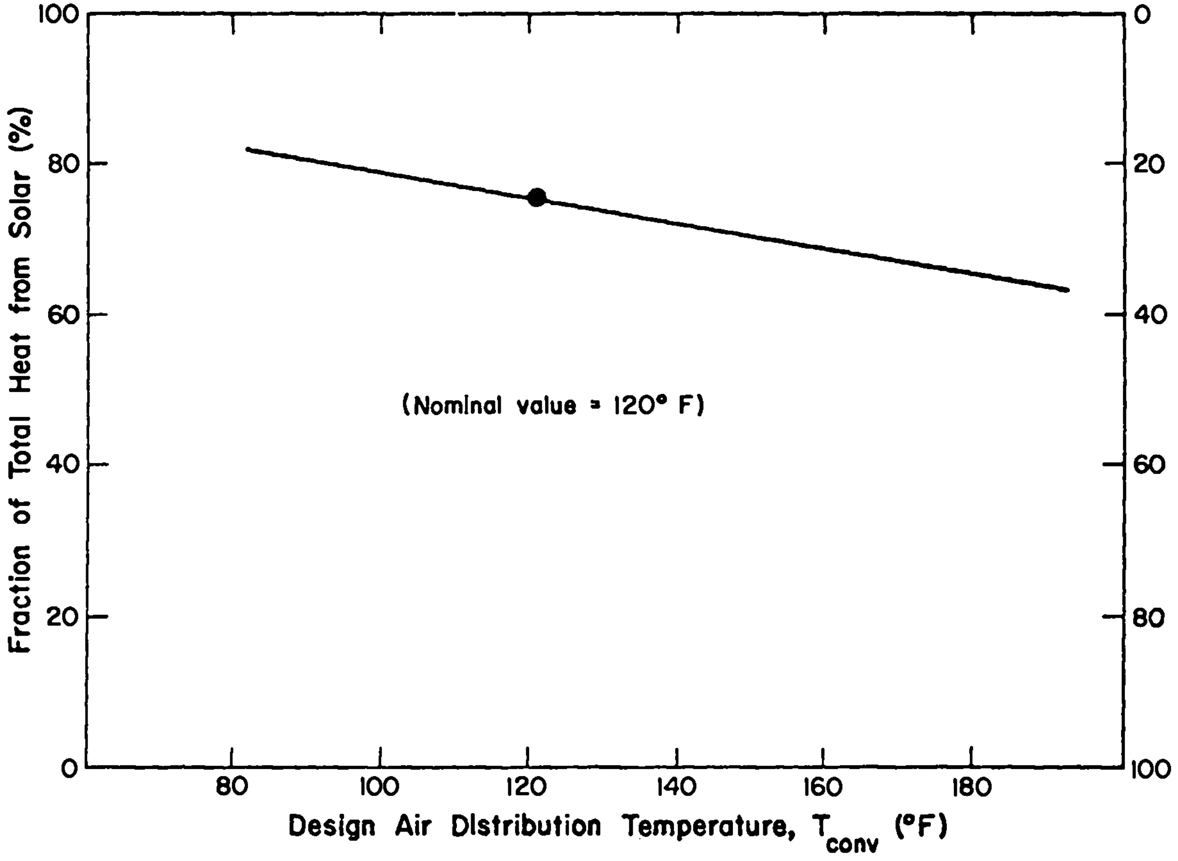
A finned-tube coil is used to transfer heat from the solar heated water to the building air. The air flow requirement of the building is a function of the design air distribution temperature. As this design temperature is decreased, the required air flow is increased and the solar heating system performance is increased—at a higher capital and operating cost. The graph shows the performance part of this tradeoff.

$$\mathrm{CFM/ft_h^2} = \frac{\mathrm{(LOAD)\,(DESIGN\ \Delta T)}}{0.82^{*}\ (T_{conv} - 68)}$$

$$= 0.82\ \mathrm{CFM/ft_h^2} = 1.64\ \mathrm{CFM/ft_c^2}\ \text{for nominal case}$$

*This is $\rho c_p \times 60 = 0.82$ BTU/CFM/°F/hr in Los Alamos (7200' elev.)

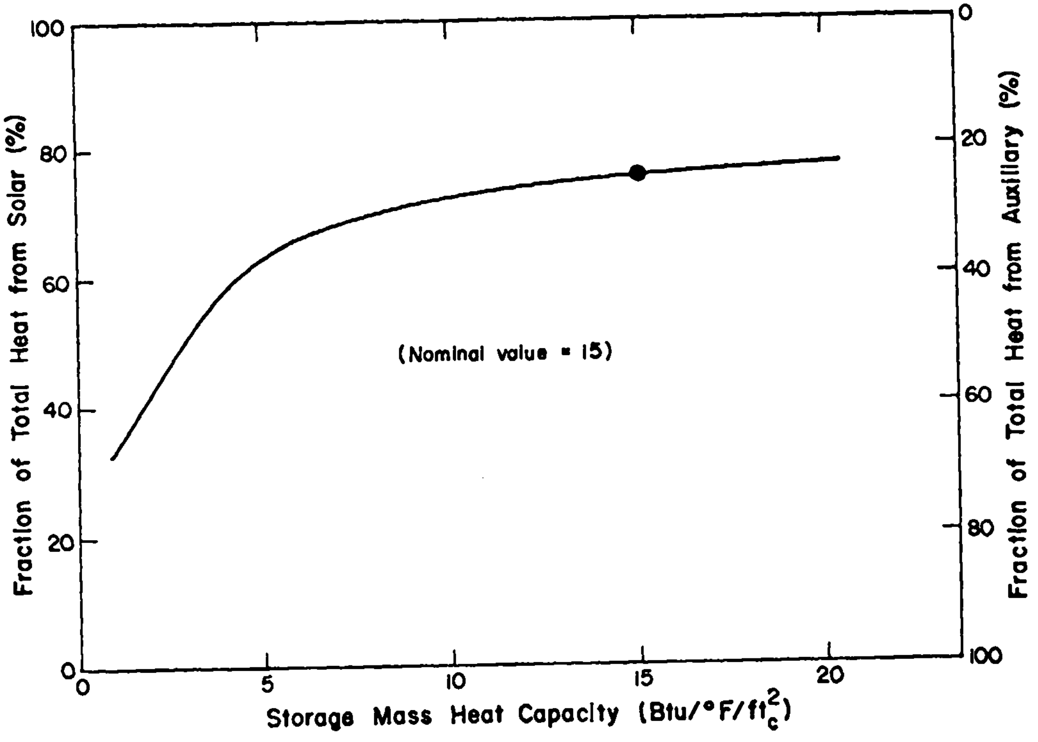
Liquid/Water/Forced Air Space Heating System in Los Alamos
EFFECT OF DESIGN AIR DISTRIBUTION TEMPERATURE



Thermal storage is desirable in a solar heating system to provide energy during those times when the sun is not shining—at night and during cloudy periods. The nominal storage mass assumed is 15 BTU/ft$_c^2$/°F (1.8 gal of water/ft$_c^2$). This is sufficient to *fully* heat the building only for 8.8 hrs. assuming an initial storage temperature of 173°F, and an outside temperature of 0°F. After this time energy would continue to be extracted from storage but an increasing amount of auxiliary heat would be required to maintain an inside temperature of 68°F.

The simulation analysis indicates that the effect of storage mass on overall system performance for the given year is relatively weak compared to some other design parameters. However, fairly severe performance losses are predicted if the storage mass is less than 5 BTU/ft$_c^2$/°F (0.6 gal of water/ft$_c^2$). Extra storage mass is relatively inexpensive and provides some extra feeling of security.

Liquid/Water/Forced Air Space Heating System in Los Alamos
EFFECT OF WATER STORAGE MASS



DESIGN PARAMETERS OF THE AIR/ROCK/AIR SYSTEM

Parameter	Nominal Value
Collector area ratio	0.5 ft_c^2/ft_h^2
Collector design:	
Number of glazings	1
Glass absorption	6% normal*
Glass reflection	8% incidence
Back insulation R	12°F·hr·ft_c^2/BTU
Air flow rate	2 CFM/ft_c^2
Collector length	10 ft
hA**	6 BTU/°F/hr/ft_c^2
Solar absorptivity	0.98 (good flat
IR emissivity	0.89 black paint)
Heat capacity	0.3 BTU/°F/ft_c^2
Tilt	45°
Orientation	due south

Parameter	Nominal Value
Storage:	
Mass heat capacity	15 BTU/°F/ft_c^2
Heat loss	(no net loss)
L/λ***	15
Distribution system:	(forced air)
Air flow rate	2 CFM/ft_c^2
Building load:	12 BTU/°F/day/ft_h^2 (68°F maintained)

*These values apply for normal incidence on ordinary double strength glass (1/8"). For other angles of incidence the Fresnel equation is used.

**The heat transfer effectiveness, hA, is the product of the effective heat transfer coefficient times the effective heat transfer area to the air coolant. It is normalized to one sq ft of collector (ft_c^2).

***L/λ is the length of the rock bed, L, divided by the relaxation length for heat transfer, λ. See page 48 .

PERFORMANCE

For the chosen nominal design parameters, the calculated yearly energy flow summary is as follows:

Total energy load	207,000 BTU/ft_c^2	100%
Energy supplied from storage	151,000 BTU/ft_c^2	73%
Energy supplied from auxiliary	56,000 BTU/ft_c^2	27%

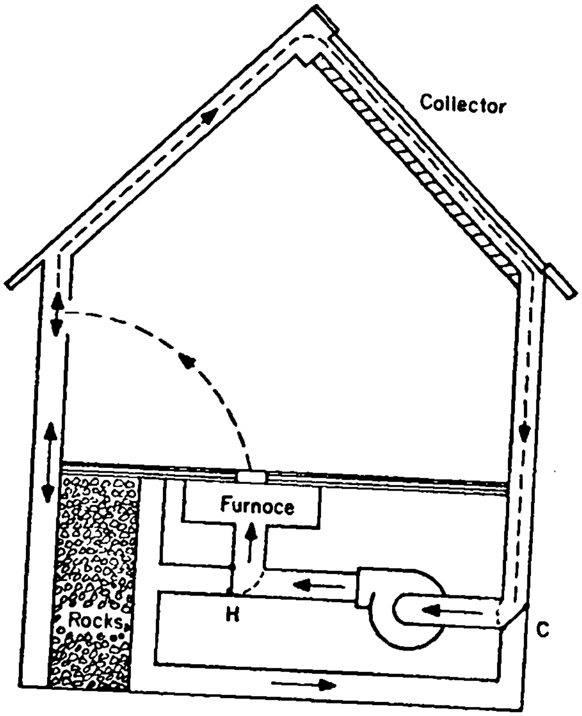
SYSTEM SCHEMATIC

The system requires only one fan and two double-dampers.

When the collector temperature exceeds the rock bed exit temperature (left side), the collector is on and Damper C is in the position shown. Otherwise the collector is off and Damper C is in the upper position.

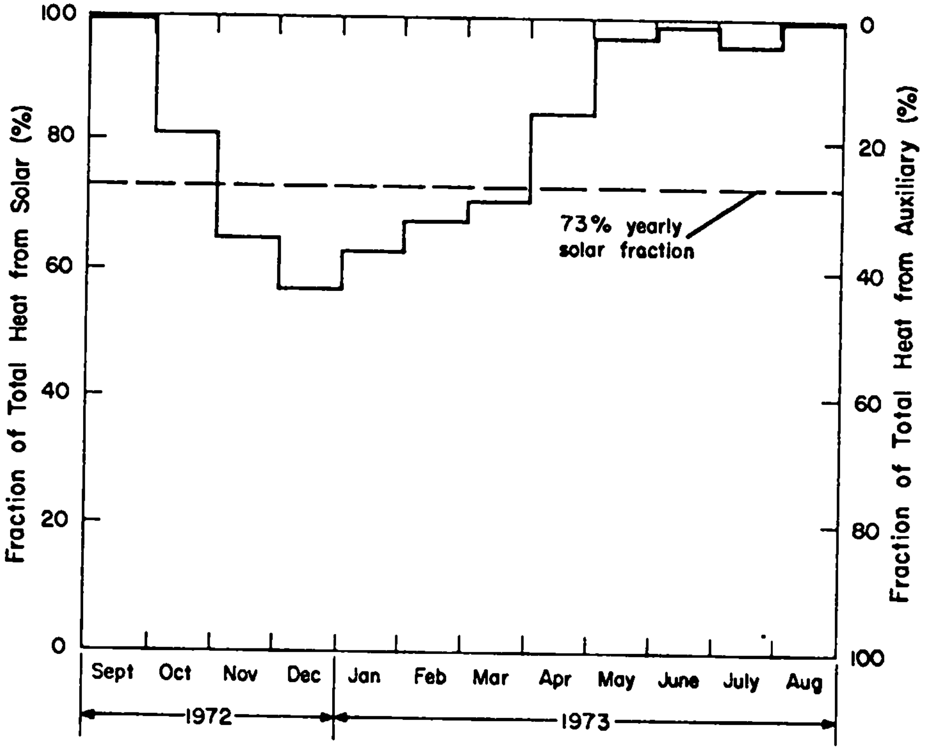
When the building calls for heat the damper H is in the position shown. Otherwise the damper H is in the upper position. The furnace is operated as necessary to satisfy the building load. The fan is on when either the collector is on or the building needs heat.

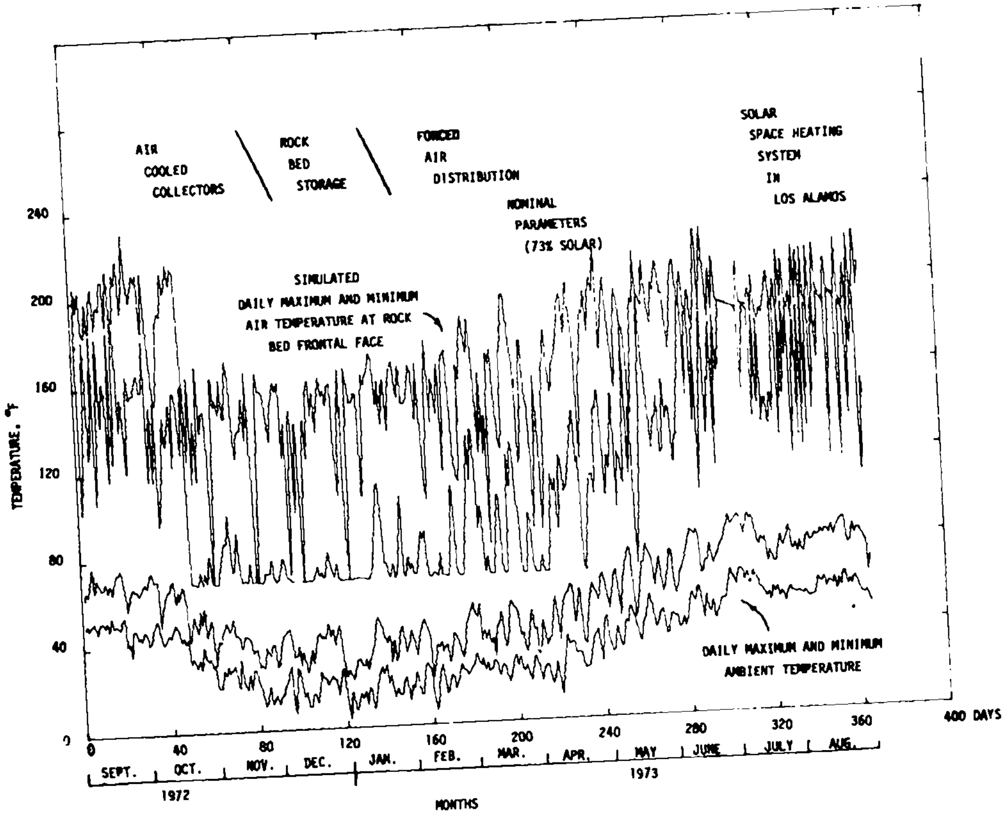
When the collector is on, the solar heated air is routed either to the building space directly (when the building needs heat) or to the rock bed. When the collector is off, the building is heated by blowing air through the rock bed in the reverse direction and directly into the building space.



Air Cooled Collectors / Rock Bed Storage / Forced Air Distribution

Air/Rock/Air System in Los Alamos
SOLAR HEATING FRACTION BY MONTH



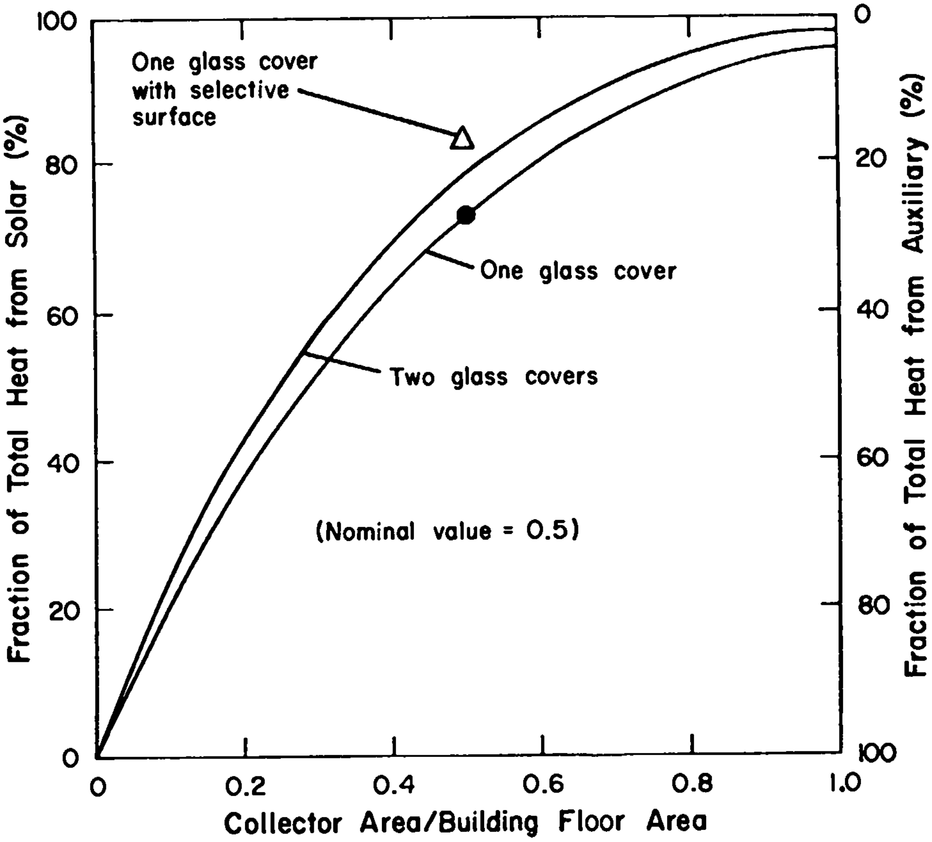

AIR COOLED COLLECTORS
ROCK BED STORAGE
FORCED AIR DISTRIBUTION
SOLAR SPACE HEATING SYSTEM IN LOS ALAMOS
NOMINAL PARAMETERS (73% SOLAR)
SIMULATED DAILY MAXIMUM AND MINIMUM AIR TEMPERATURE AT ROCK BED FRONTAL FACE
DAILY MAXIMUM AND MINIMUM AMBIENT TEMPERATURE
TEMPERATURE, °F
0
40
80
120
160
200
240
0
40
80
120
160
200
240
280
320
360
400 DAYS
SEPT.
OCT.
NOV.
DEC.
JAN.
FEB.
MAR.
APR.
MAY
JUNE
JULY
AUG.
1972
1973
MONTHS

This graph can be used to determine either the required collector array size to achieve a desired performance with a given load or the effect of changes [illegible] load with a given collector area. A nominal building load of 12 Btu/ft^2/ °F/day was assumed. If the building load is different than this then the collector-to-building area ratio can be scaled proportionally.

The effect of double glazing is to reduce the collector heat losses. However, it also reduces the sunlight reaching the absorber surface and increases the collector cost.

The single point labeled "selective surface" was calculated with a collector absorber surface absorptance of 0.9 and emittance of 0.10. The performance increase over a flat black paint is to increase the solar fraction from 73.0% to 82.3%. It is instructive to note that the solar fraction with two sheets of glass over a selective surface is 81.3%. This decrease in performance is because the performance gain due to absorption and reflection in the extra sheet of glass exceeds the performance gain due to decreased convection losses.

Air/Rock/Air System in Los Alamos
EFFECT OF COLLECTOR ARRAY SIZE

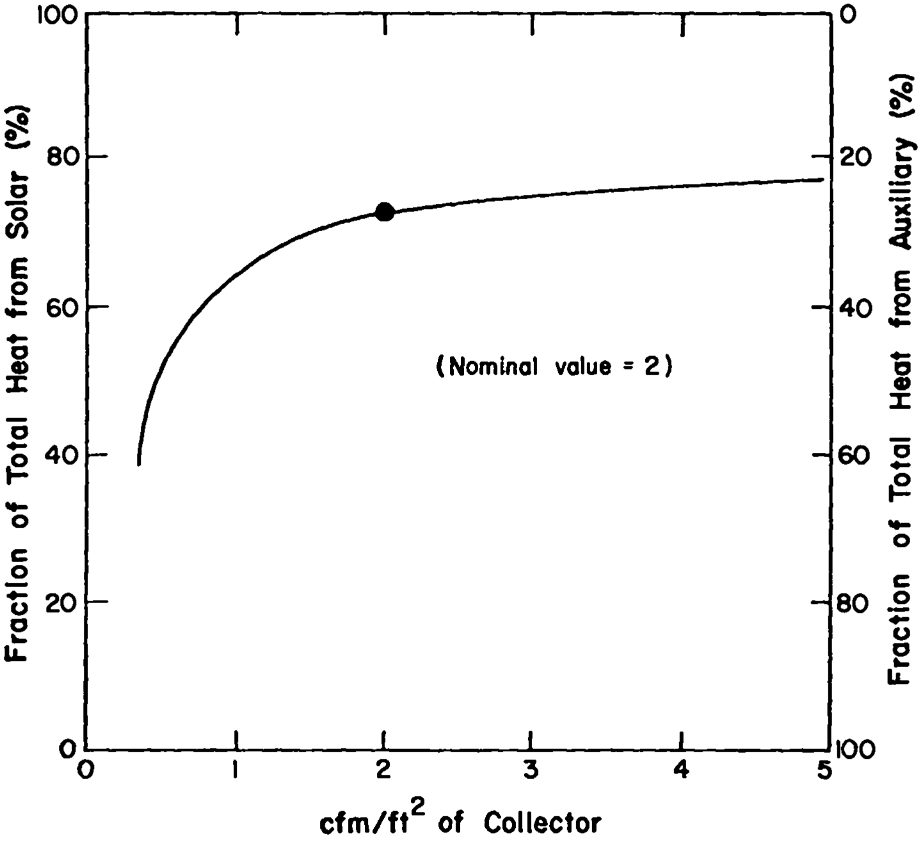


Air flow rate is a very important parameter because as the air flow decreases the collector ΔT increases and collector efficiency decreases. A severe performance penalty will result at air flow rates below 1 cfm/ft_o^2

Note that the variation in air flow rate is made assuming that the parameter hA is constant at a nominal value of 6. Since h is dependent on flow rate in a collector of fixed geometry, holding hA constant implies changing collector geometry as air flow rate is changed. This confusion is unraveled somewhat by the chart on page 43.

Air/Rock/Air System in Los Alamos

EFFECT OF AIR FLOW RATE

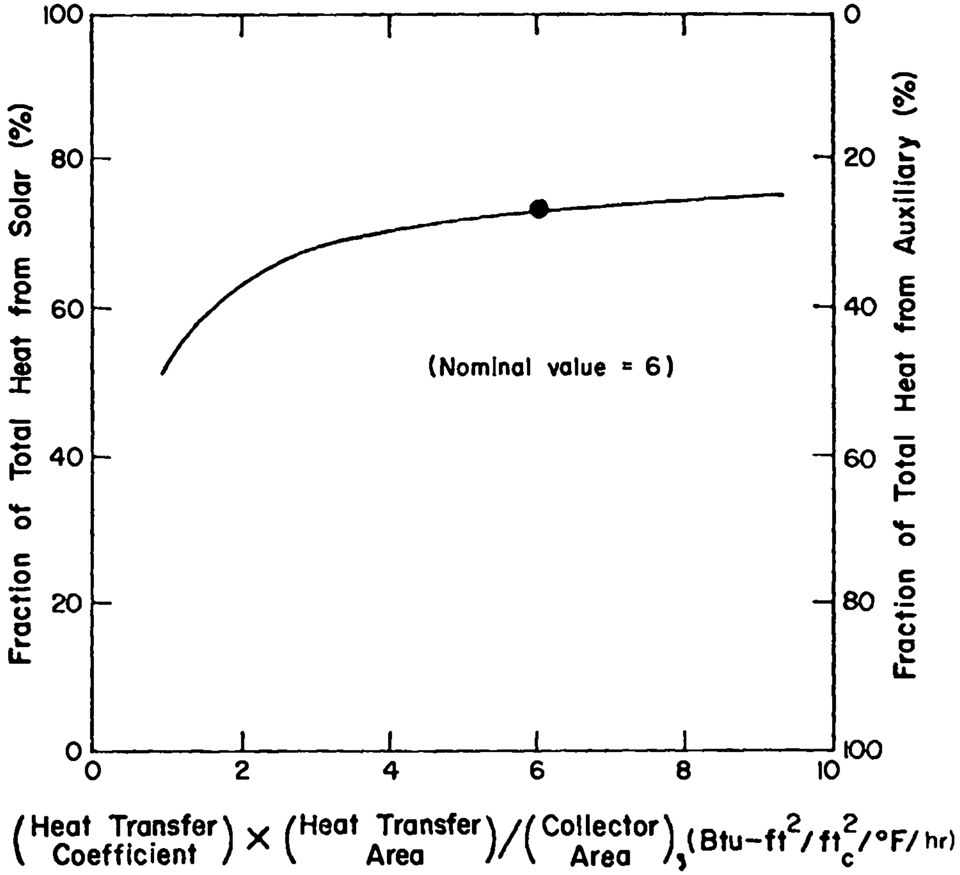


The other important collector parameter is the heat transfer effectiveness, hA. This is the product of the heat transfer coefficient times the heat transfer area divided by the collector area. The area, A, can be increased by adding fins or making all sides of the flow passage effective for heat transfer. The heat transfer coefficient can be increased by increasing the flow velocity and decreasing the flow channel size.

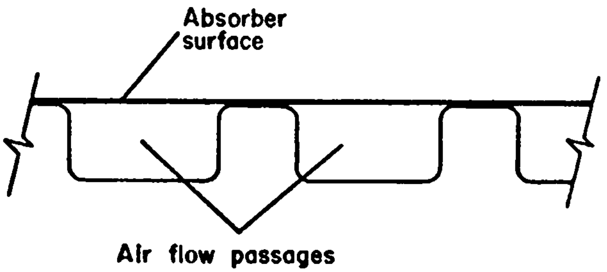
Note that the variation in hA is made assuming that air flow rate is constant at the nominal value of 2 $\mathrm{cfm/ft}_c^2$.

Air/Rock/Air System in Los Alamos

EFFECT OF COLLECTOR HEAT TRANSFER EFFECTIVENESS



There are many ways to design an air cooled solar collector. One effective geometry is shown here:

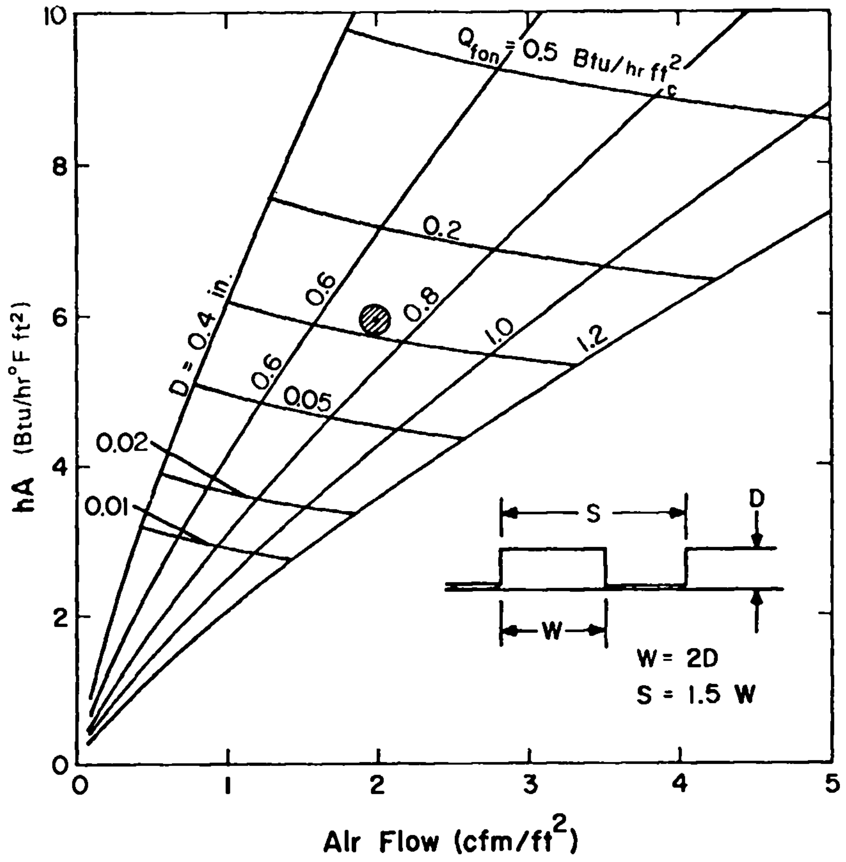


All sides of the air flow passages are effective for heat transfer since the two metal plates are touching and therefore in thermal contact.

The design chart indicates that a nominal value of hA = 6 at an air flow rate of 2 cfm/ft^2_c can be obtained in a 10 ft long collector with values of D = 0.70'', S = 2.10 in. and W = 1.40 in. For these conditions the flow velocity is 514 feet per minute, A is 2 ft^2/ ft^2_c and h is 3 Btu/ft^2/hr/°F.

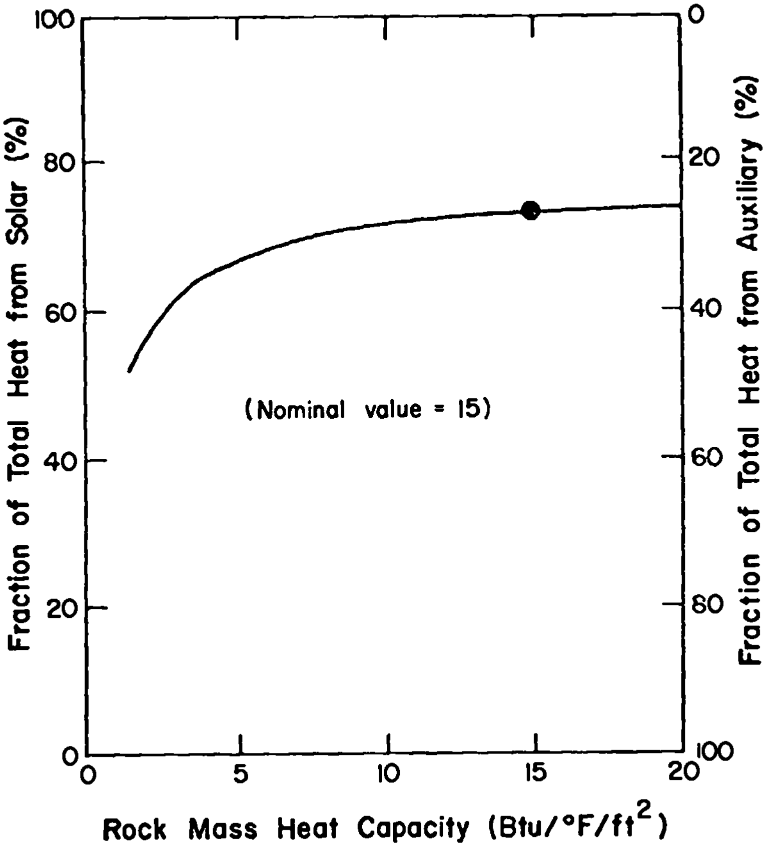
Increases in hA increase the collector pressure drop and therefore increase the required fan power. For the nominal values chosen, the collector pressure drop is 0.075 in. of water and the pumping energy lost in channel friction is about 0.12 Btu/ ft^2_c/hr or 0.035 watts/ft^2_c. This number is quite small even factoring in inefficiencies for the motor and fan.

AIR COLLECTOR PERFORMANCE MAP, L=10FT



The effect of the size of the thermal storage is not very important beyond a value of about 5 BTU/°F/ft_c^2 corresponding to 24 lbs of rock/ft_c^2. The nominal value of 15 BTU/°F/ft_c^2 corresponds to 71 lbs of rock/ft_c^2. This requires roughly three times the volume of water storage or about 0.75 ft^3/ft_c^2. Most rock has a specific heat of about 0.21 BTU/lb/°F, a density of about 165/lb/ft^3, and packs with a void fraction of about 0.42 if the rocks are all roughly the same size.

Air/Rock/Air System in Los Alamos
EFFECT OF ROCK STORAGE MASS



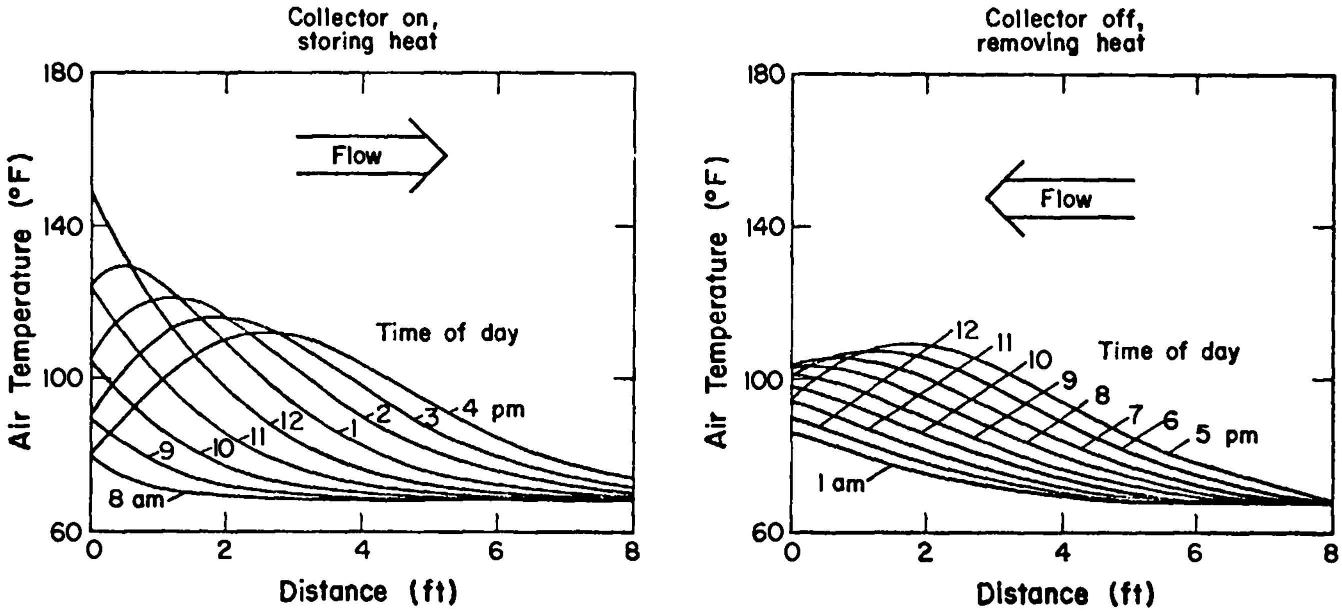
A rock bed is an efficient heat transfer device. The air quickly gives up its heat in flowing through the labyrinthine path. As a result the rocks near the air entry end of the bed can be at quite different temperature than rocks near the air exit end. This time dependent spatial temperature distribution must be accounted for in the simulation analysis.

A simplified illustration is given on the plot. We assume the bed is cold in the morning. As the day progresses the air temperature from the collector rises, peaks at noon, and decreases in the afternoon. The resulting air temperature distributions in the rock bed are shown at different times during the day. Note that the exit air from the bed is always cold and therefore the collector operates at high efficiency all day.

In the evening, when the collector is off and the building needs heat, the air flow direction through the bed is reversed so that the air exits from the hottest part of the bed. (If the air flow were not reversed, then one would have to wait hours to wash the heat through the bed and even then would get only moderately warm air.) As the evening progresses the temperature out of the bed rises until 8:00 o'clock and then falls, resembling the time profile of the inlet temperature during the day, but in reverse.

In the simulation analysis, this detailed temperature distribution is determined each hour of the year by dividing the rock bed into eleven axial zones and calculating the temperature of each zone. The temperature plot on page 35 is for the air temperature at the bed frontal face corresponding to the right hand side of the rock bed shown in the diagram on page 33.

ROCK BED TEMPERATURE DISTRIBUTIONS



Collector on, storing heat

Collector off, removing heat

For a fixed rock bed volume the length can be varied by varying the frontal area. Generally speaking a short, flat bed is preferable to a long, skinny bed because of pressure drop considerations. If the length is decreased below a value of about 3λ, then a significant performance penalty is incurred because the spatial temperature distribution benefits described on page 46 become ineffective. The parameter λ is the relaxation length for heat transfer in the bed. It is given by the equation:

$$\lambda = \frac{\dot{W} c_p L}{h A}$$

where: h = heat transfer coefficient, air to rock

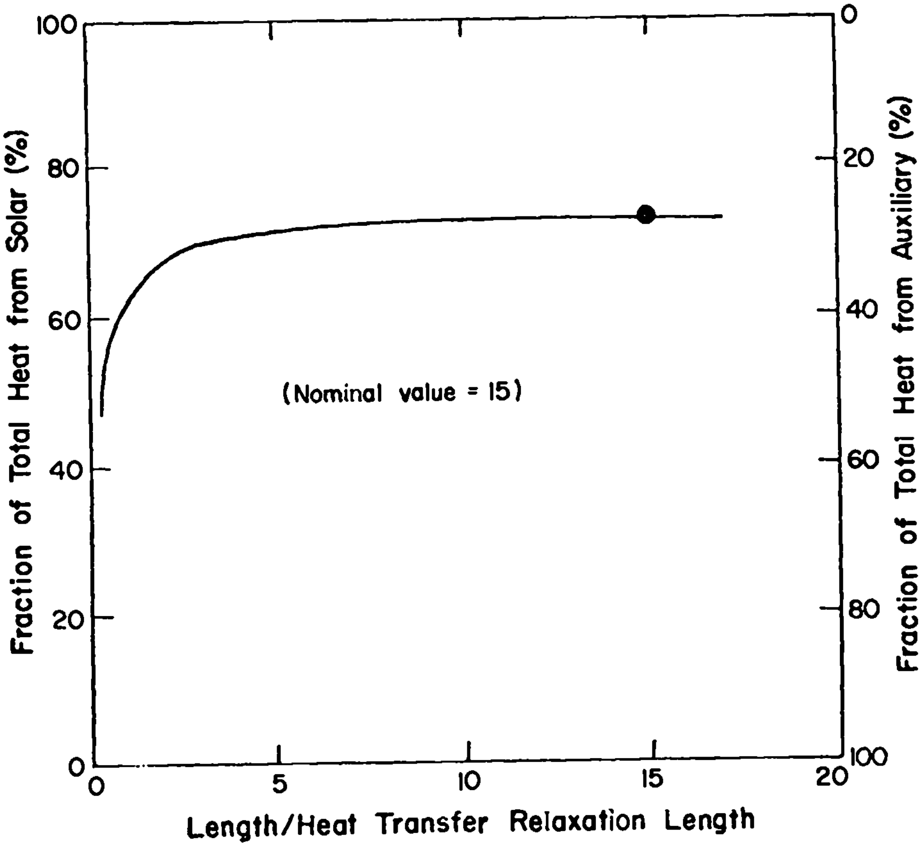
A = rock surface area

L = bed length

c_p = air heat capacity

$\dot{W}$ = air mass flow rate

The parameter λ has units of length.



Air/Rock/Air System in Los Alamos
EFFECT OF ROCK BED LENGTH

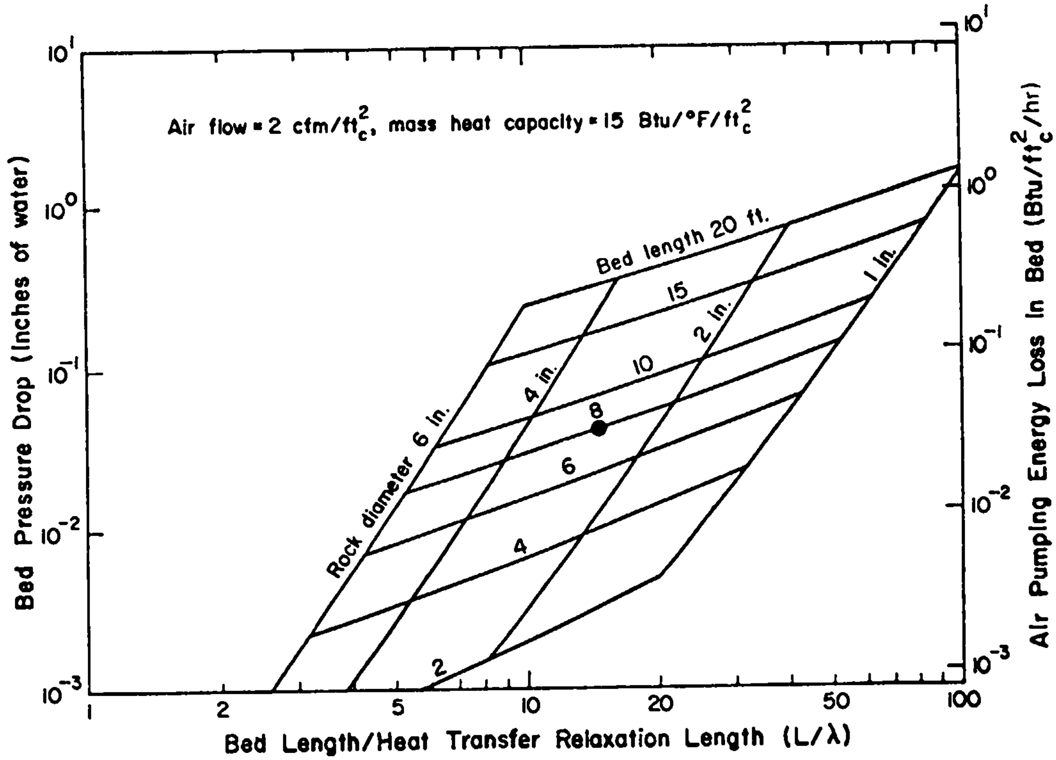
The previous analysis parameters, λ and air flow rate, can be related to the real parameters of interest to the builder—rock size, bed length, and pressure drop, through a performance map.

The nominal parameters chosen correspond to a rock size of 2.7 inches and a bed length of eight feet. For this rock size and flow rate, the value of λ is 6.4 inches. Since the bed length is not important beyond a value of 5λ the builder has great flexibility in arranging the rock bed within the structure.

Excessive rock bed pressure drop can lead to excessive fan power requirements. For the nominal case chosen the pressure drop is 0.04 inches of water corresponding to a pumping energy lost in rock bed friction of 0.032 Btu/ft^2/hr or 0.01 W/ft^2. This number is quite small even after factoring in fan and motor inefficiencies.

Rocks of uniform size should be used to avoid small rocks filling in the interstices between the large rocks and thereby increasing the bed resistance to air flow.

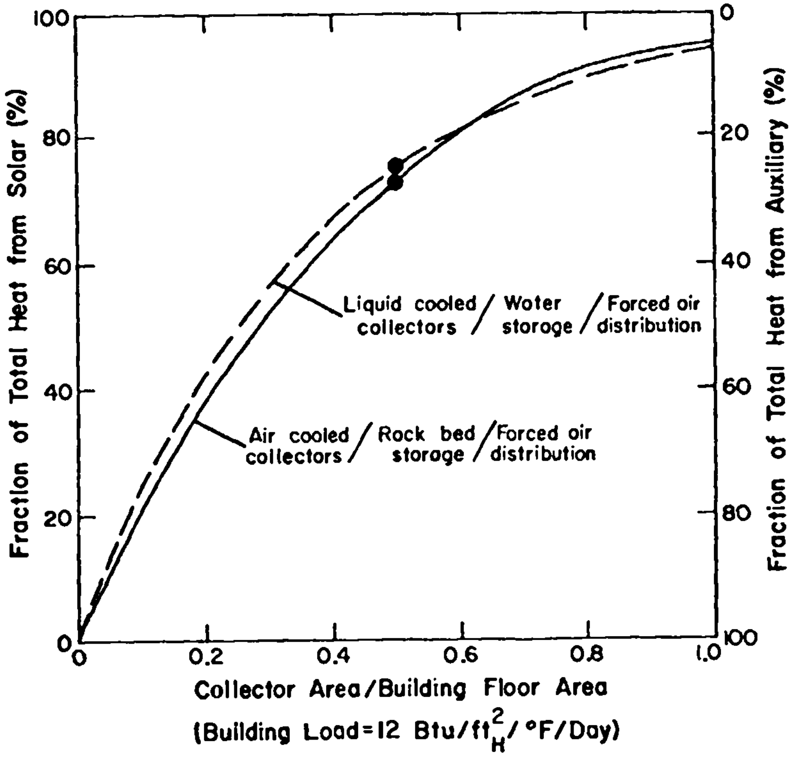
ROCK BED PERFORMANCE MAP



This plot shows a comparison between the performance of the air/rock/air and a liquid/water/air system as a function of collector-to-building area ratio based on nominal parameter selections for each system. Clearly there is little to choose between the two based on performance alone. One could change the nominal parameters slightly to give a small performance edge to either system. Thus the actual choice between these competing system design concepts will probably rest on considerations other than pure performance. These other considerations may be cost, ease of installation, maintainability, convenience, availability, philosophy, or prejudice. In any case, the system should be designed in accordance with good engineering principles to yield an optimum or near optimum installation based on all considerations.

COMPARISON OF SPACE HEATING SYSTEMS

(Nominal Parameters Selected for Each System)



DOMESTIC HOT WATER HEATING

Compared to space heating, domestic hot water heating requires a relatively small amount of energy and therefore requires a correspondingly smaller solar collector array. Although not explicitly considered in the simulation analysis, domestic hot water heating is a natural and almost universal add-on to a space heating system of either basic type.

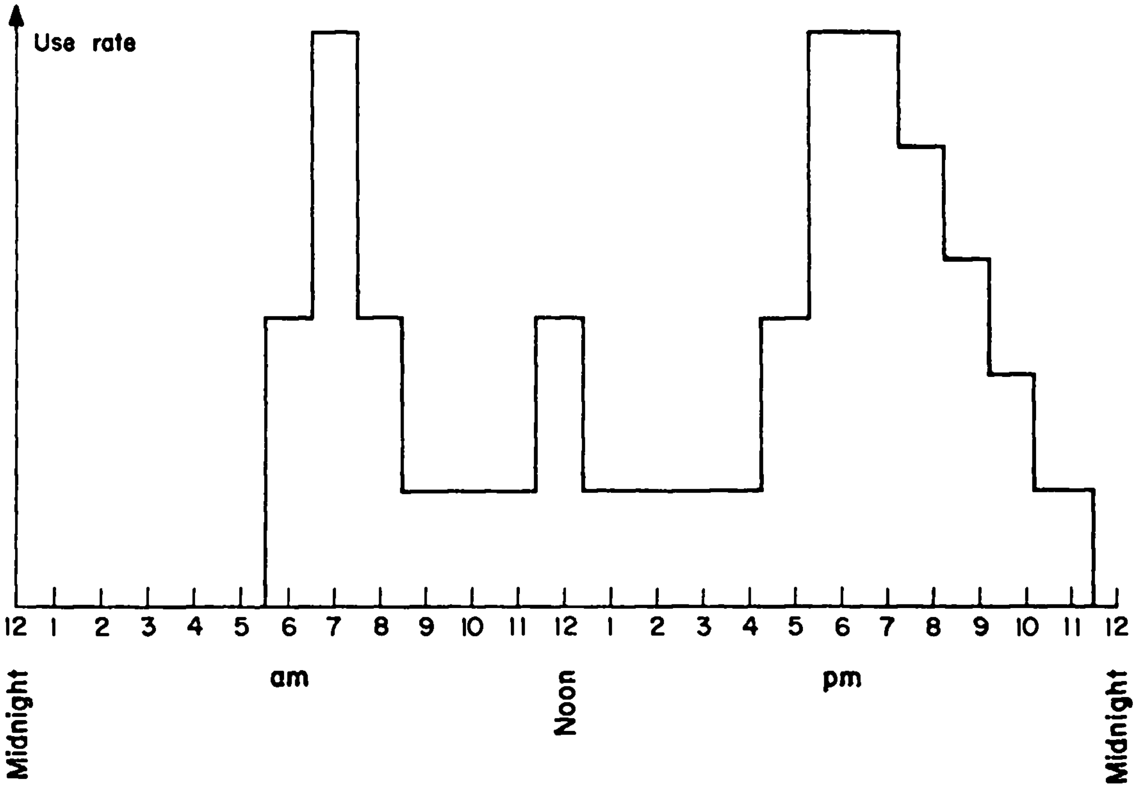
Liquid cooled collector designs enjoy a natural advantage in a situation where only domestic hot water is generated because there is no liquid-to-air transfer required anywhere within the system. A liquid-to-water heat exchanger is considered desirable in Los Alamos due to the desire to avoid a water cooled collector and the associated problems of freezing, corrosion and scaling.

The thermal load is quite different for water heating than for space heating. An assumed profile of hot water demand was deduced based on personal experience and estimation. The simulations were run for this profile. The profile is assumed to be the same for every day of the year.

The nominal design parameters for the collector are the same as those given for the liquid/water/air system on Page 18. Since the storage tank is relatively small, the heat loss from the tank surface is relatively larger than for a space heating system and is explicitly accounted for in the analysis. A tank surface of 0.5 ft^2/ft_c^2 is assumed with a tank insulation resistance of 12 $ft^2 \cdot hr \cdot °F/Btu$.

A nominal load was assumed equal to one gallon of 120 °F water per day per square foot of collector. A simple (but non-optimum) control scheme was adopted in which auxiliary heat is added as necessary to maintain the storage temperature at 120°F.

ASSUMED USE PROFILE FOR DOMESTIC HOT WATER



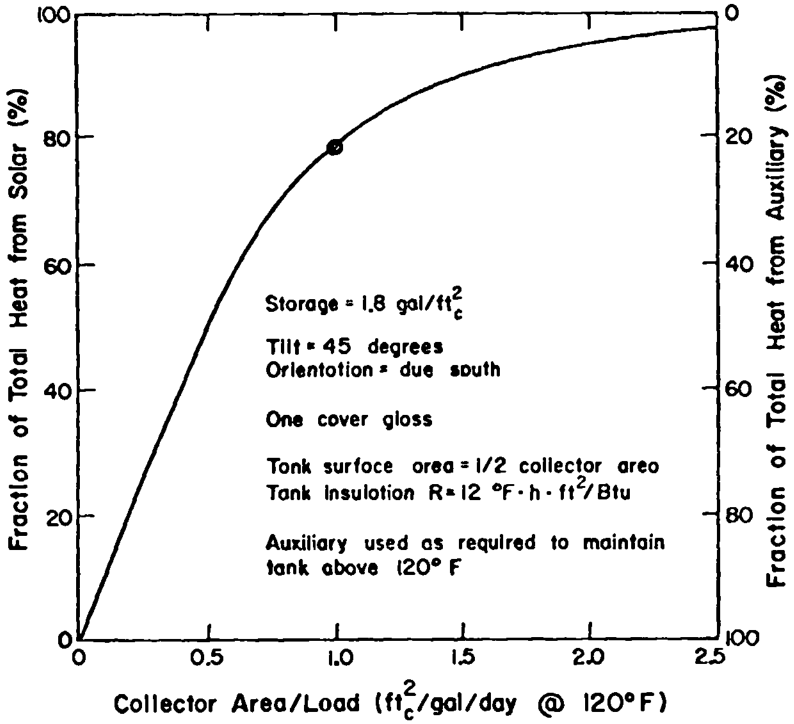
As in the situation of a space heating system, the ratio of the collector size to the thermal load is the single most important design parameter for domestic hot water heating. For hot water heating the load is given in gallons/day (at a temperature of 120°F) per ft^2 of solar collector. The inlet water temperature is assumed to be 60°F.

For the nominal case the energy sums are as follows: (for 1 ft^2 of collector).

Month	Load, KBTU/mo.	Solar, KBTU/mo.	Auxiliary, KBTU/mo.
Sept.	15.01	17.13	.70
Oct.	15.51	11.61	5.30
Nov.	15.01	12.98	4.16
Dec.	15.51	12.10	5.13
Jan.	15.51	14.88	2.70
Feb.	14.01	12.39	3.72
Mar.	15.51	12.27	5.01
Apr.	15.01	14.32	2.61
May	15.51	13.25	4.21
June	15.01	16.04	1.54
July	15.51	14.45	2.73
Aug.	15.51	17.27	.80
TOTAL	182.6	168.7	38.61

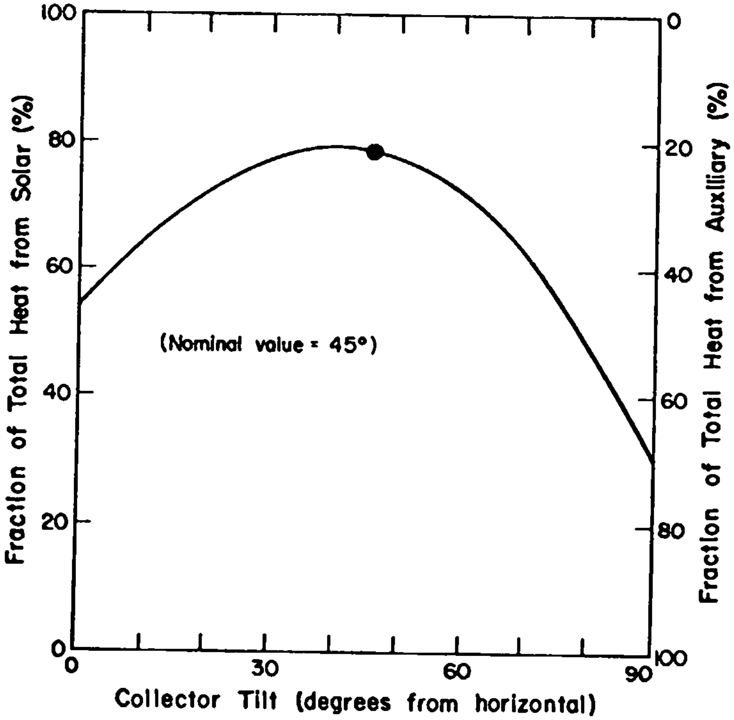
The losses from the tank are 24.7 KBTU/year (12%)

Domestic Hot Water System in Los Alamos
EFFECT OF COLLECTOR ARRAY SIZE



The effect of collector tilt for domestic hot water heating is quite different than for liquid/water/air space heating because of the constancy of the load. The optimum tilt appears to be about 42°. The performance falls markedly at tilts below 20° or above 60°.

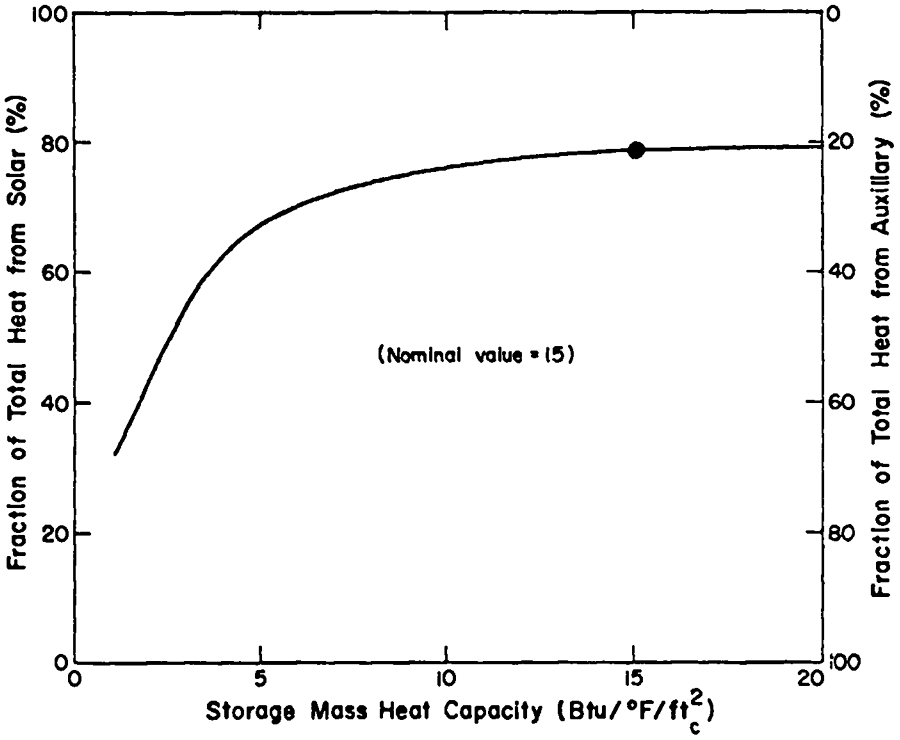
Domestic Hot Water System in Los Alamos
EFFECT OF COLLECTOR TILT



The effect of storage mass for domestic hot water heating is very similar to the effect of storage mass in a liquid/water/air space heating system but drops off somewhat more rapidly at values below 5 Btu/°F/ft^2. At a value of 15 Btu/ft^2/°F there is nothing to be gained by further increases. The heat loss from storage is made proportional to the tank surface area by using the relation:

$$\frac{\text{Tank Surface Area}}{\text{Collector Area}} = 0.5 \left(\frac{\text{Storage } MC_p}{15} \right)^{2/3}$$

Domestic Hot Water System in Los Alamos
EFFECT OF WATER STORAGE MASS



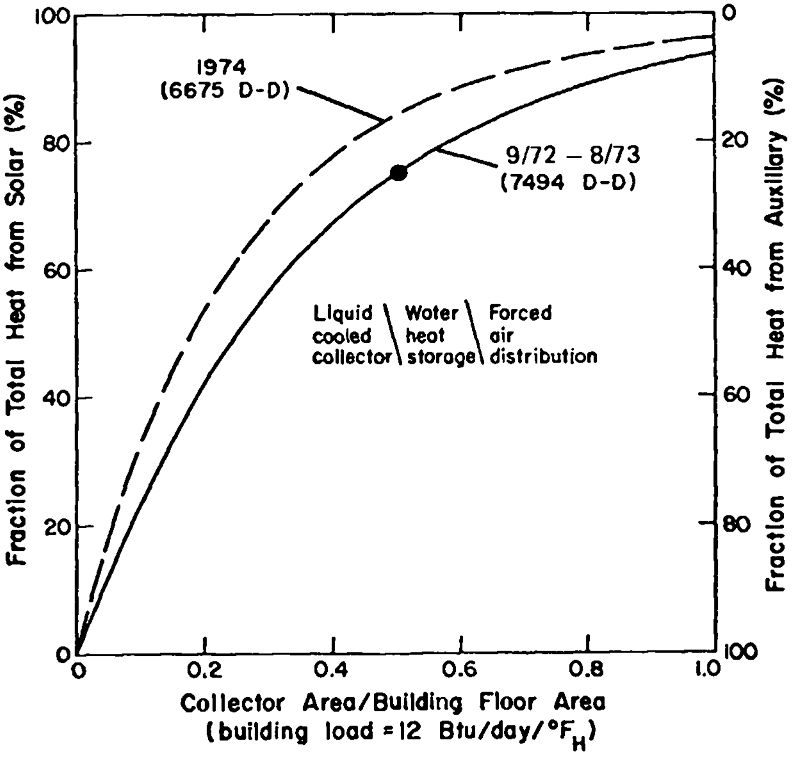
Year-to-year variations in system performance should be expected as a result of variations in the local climate —both as to temperature and solar radiation. The study presented herein is based on a long heating season which extended further into the spring than normal. Severe low temperatures were not experienced, however the average temperature was significantly lower than normal. The integrated heating load, based on a 65°F inside temperature, was 7494 degree-days, compared with an average Los Alamos value of 6350 degree-days. Integrated solar radiation was believed to be significantly less than normal although insufficient records are available to establish an average value.

Data taken for calendar year 1974 have been compiled and a few simulation analyses have been made. The performance of the solar energy system is markedly improved compared to the nominal year. The plot on the opposite page shows the comparison. The integrated heating load and solar radiation values are as follows:

Year	Heating Load, Degree-Days	Solar Radiation (45° Tilt)
		$BTU/ft^2/yr$
9/72 – 8/73	7494	586,000
1/74 – 12/74	6675	659,000
Normal	6350	Unknown

It is believed that 1974 is much more typical of what one could expect in Los Alamos than the nominal year. However, if one designs the system for a difficult year then the system should work better for easier years.

Severe cold weather conditions sometimes occur in Los Alamos —minus 20° and colder. These periods usually occur during clear sky conditions when the night-time radiant heat loss from the earth is very high. Since useful solar heat can be collected each day, these periods usually will require less auxiliary heat than moderately cold periods of extended cloudiness.


1974
(6675 D-D)
9/72 – 8/73
(7494 D-D)
Liquid cooled collector \ Water heat storage \ Forced air distribution
Fraction of Total Heat from Solar (%)
Fraction of Total Heat from Auxiliary (%)
Collector Area/Building Floor Area
(building load = 12 Btu/day/°F$_H$)
0
20
40
60
80
100
0
0.2
0.4
0.6
0.8
1.0
0
20
40
60
80
100

SUN-TEMPERED BUILDINGS

Sun tempered buildings may be characterized as a limited application of the passive systems concept. There are energy flows that occur in nature without human intervention. When we divert these flows to our benefit without the direct application of energy we have produced a passive system. In the real world it is frequently advantageous to apply a small amount of energy to divert a large energy flow, in such cases we refer to the system as being "highly passive".

In dealing with building systems for heating and cooling we are primarily concerned with the energy flux from the sun and radiation that flows from the earth to the night sky. There is a tendency to ignore the latter and concentrate on the solar flux. However, we note that the heat balance of the earth is very near to zero*, and must conclude that the flow of energy from the earth to outer space is a flux that we should utilize.

There are a numher of passive elements or mechanisms that may be applied to both passive and active systems to conserve energy. Some are tabulated on the opposite page with a few typical applications.

Passive systems have emerged, and there are enough sun tempered buildings now in use to demonstrate the concept and allow us to examine the interaction between the dwelling and the dwellers. Most of these first generation buildings are private residences or small shops. In general, they represent a high level of ingenuity and intuitive empiricism in their design.

Some examples of sun tempered structures as they now exist in everyday use are given on the following pages.

*Budyko, "The High Balance of the Earth's Surface". Leningrad, 1956

ELEMENTS OF SUN-TEMPERED BUILDING DESIGN

ELEMENT	APPLICATION
Radiation:	a) In heating, radiation can be used as a transport mechanism for removing heat at low temperature from another passive element such as a storage wall. b) In cooling, radiation can be used to remove heat from a structure by radiation to the night sky.
Insulation:	a) Movable insulation can be used in highly passive systems to divert energy flows. b) Static insulation may be applied to establish the direction of energy flows by blocking a natural flow path.
Heat of Fusion:	a) In heating, phase change materials offer a promising energy storage mechanism. b) In cooling, phase change materials offer a promising thermal energy sink.
Fenestration:	Windows can be used to admit solar radiation either to warm the structure or for lighting.
Evaporation:	Static outdoor ponds can be evaporatively cooled and the remaining water used to cool the space. Spraying or cascading water increases the evaporation rate and can have a pleasing side effect.
Air Stratification:	a) Stratified air can be vented to reduce air conditioning loads. b) Stratification can be used to concentrate warm air for use elsewhere.
Building Structural or Added Mass:	a) Mass provides natural thermal storage. b) Materials of high mass and low thermal diffusivity can delay the arrival of a thermal wave until the heat can be used effectively.
Natural Convection:	a) In air systems natural convection can be used as a heat transport mechanism and to produce air movement (ventilation). b) In liquid systems natural convection can be used to transport heat as in a thermosiphon hot water heater.
Shading:	Roof overhangs can be designed to admit the low winter sun and block out the high summer sun (the "Mesa Verde effect"). The noon-sun elevation angle change from summer to winter is 47 degrees.

THE STEPHEN BAER HOUSE,CORRALES,NM

This house is located on a south facing slope in the sand hills northwest of Albuquerque, New Mexico.

The architecture is singular and the construction unique. The design is based on a crystal form developed by Baer. Each form defines a space, and spaces may be combined by adding another form at a congruent crystal face.

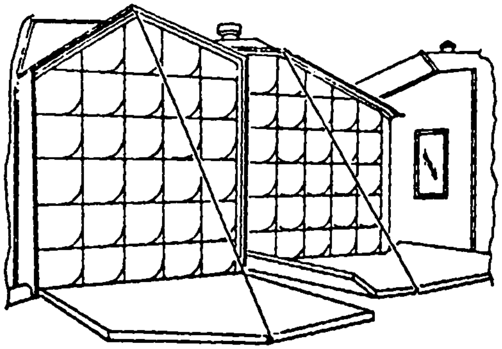
From a distance the house is seen as a bright spot of light on the rather barren Corrales sand hills. A first encounter at close range gives one pause, and the interior considered along with a partially enclosed patio is completely charming.

The solar heating and storage system consists of "drum walls". The south facing crystal terminations are truncated in a plane. On sunny days the wall rotates about its lower edge exposing a glass wall, the inner surface of the wall (now in the horizontal position) acts as a supplemental reflector. Behind the glass is a floor to ceiling rack of 55 gallon drums in a close packed horizontal array. The drums are filled with water and painted black on the side facing the glass. The inner portions of the drums are painted in light shades to complement the decorating scheme of the space they serve. Visually, from inside the building, the "drum walls" are interpreted as an architectural screen with the brightly lit spaces between the drums presenting a repetitive star shaped pattern. When the solar heating day is over, the wall is rotated into the closed position providing a thermal seal; the glass compliments this as infrared reflective insulation.

In operation, in the heating mode, the drums release heat to the space by radiation and convection. The well insulated polished aluminum inner lining of the dwelling acts as reflective insulation to the infrared component.

The system is operated in reverse in the summer.

The Baer house as seen from the east.



Drum walls shown in the exposed mode.

THE TROMBE HOUSE

The Trombe house has its origins in the solar community near Odeillo in the French Pyrenees. F. Trombe and his colleagues have constructed several houses following the general scheme sketched across page.

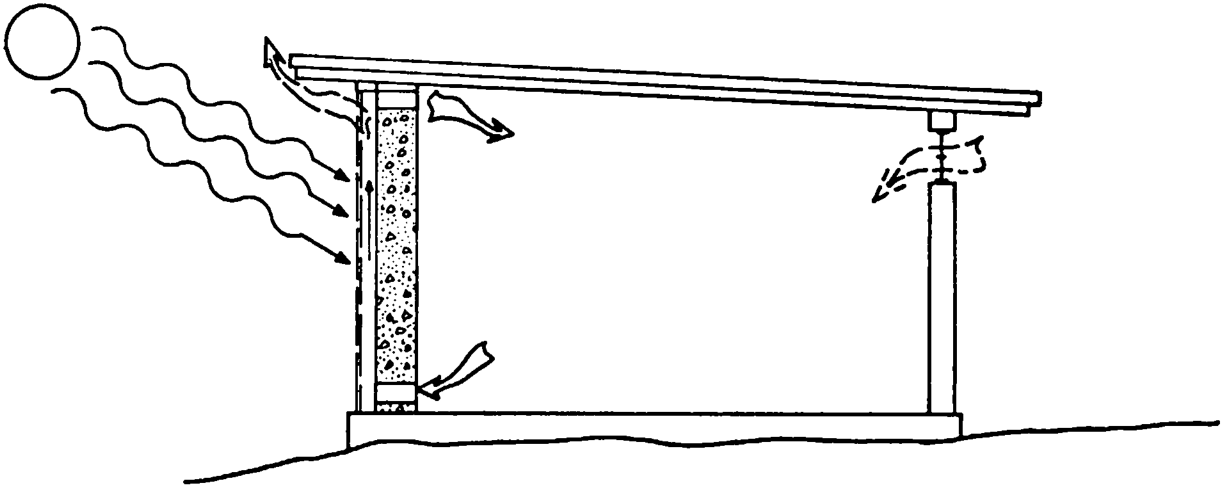
The basic passive element is a massive, south facing, concrete wall. The wall is painted black on the exterior surface and is provided with a double glazed cover. There is a space provided between the wall and the glass that serves as an air passage. Other air passages are provided through the wall near the ceiling and floor levels.

In the heating mode, insolation strikes the black wall surface which becomes hot and starts convective air flow through the passage between the glass and the wall. Air is drawn from the floor length openings and discharged into the occupied space through the ceiling level openings. Thus, a convective loop is established, heating the occupied space during the day.

Meanwhile, the wall is slowly accumulating thermal energy as a portion of the insolation diffuses into the concrete and is stored there. At night the convective loop is closed off and the concrete storage wall serves the occupied space as a low temperature radiant heating panel. As the wall is radiating in the infra-red spectrum, the exterior glass, which is opaque to this radiation, blocks radiant losses. There are, however, some convectional quasi-steady state transmission losses of heat to the outside environment.

In the summer, the overhanging roof shades the fenestration from the direct rays of the sun. The top of the collection wall system may be vented and the convective circuit may be used to ventilate the building. This path is indicated by the dashed arrows on the sketch.

Trombe has not published detailed results covering the operation of these houses; however, some experiments and full scale studies by workers in the United States indicate that the system has merit.



TROMBE HOUSE

THE DAVID WRIGHT HOUSE, SANTA FE, NEW MEXICO

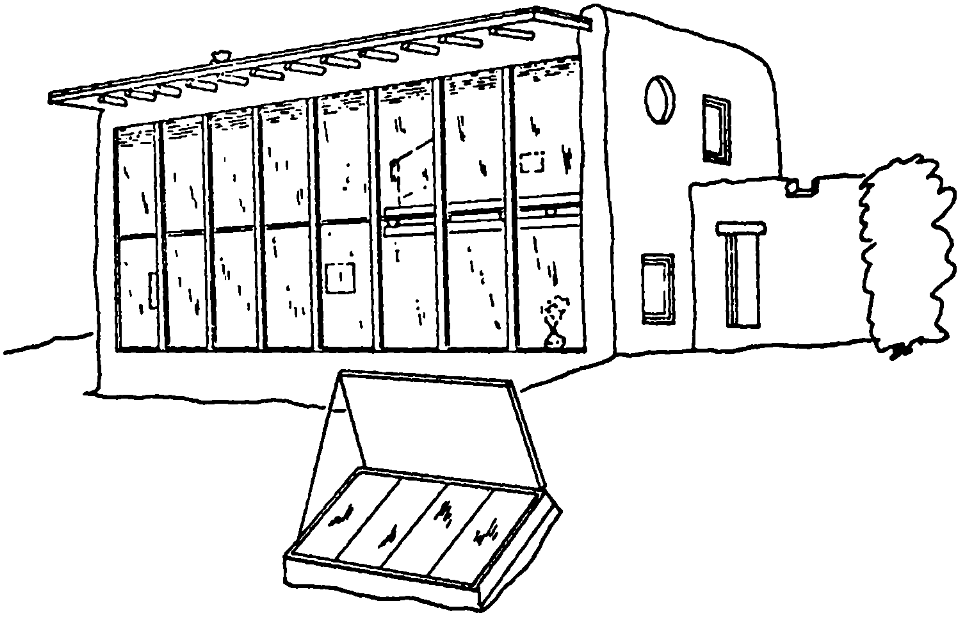
This house presents a good example of a relatively extreme commitment to a total sun tempered ethic. Architecturally the dwelling reads as a rather strong statement in the adobe idiom, counterbalanced by the harsh terrain of the pinon belt of the Sangre de Cristo range foot hills.

The basic structure is elliptical in plan with the major axis oriented along an east-west line. This simple form is softened by additional elements at the east end that provide an entry and "air lock" that avoid excessive infiltration into the primary living space.

The building is two stories high with the living room a clear story and the second floor characterized by rather open design. The south face of the building is a double glazed glass wall that rises from a few feet above the floor to the roof beam line and serves as the collector system. At night this glass area is occluded by drapes, a temporary measure while suitable insulating panels are worked out. The backup heating system consists of a wood fired Franklin stove. (A form of stored solar energy).

Thermal storage is provided by the adobe walls that are insulated by two inches of polyurethane applied to the outer surfaces and covered by a thick layer of plastic.The floor and perimeter are also insulated at depth, and there are some 55 gal drums filled with water embedded in the "banko" (a low seat, part of the structure; characteristic of Southwest architecture) under the south facing windows for additional mass. Domestic hot water is provided by a thermosiphon solar heater with the collector located on a south slope outside of the building.

The house has been occupied during the winter of 74/75 and is performing well. During the "charging"period it tends to overheat and this excess heat is disposed of by venting through windows on the second floor (included in the design for this purpose and summer ventilation). Summer insolation is controlled by roof overhang on the south side.



THE DAVID WRIGHT HOUSE

NOMENCLATURE

A = Area for heat transfer, square feet

CFM = Air volumetric flow rate, cubic feet per minute

Cp = Specific heat at constant pressure, BTU per (pound mass) (Fahrenheit degree)

h = Heat transfer coefficient, BTU per (hour) (square foot)

L = Length, feet

M = Mass, pounds

Q = Incident solar radiation, BTU per (square foot)(hour)

R = Thermal resistance, (hour)(Fahrenheit degrees) (square feet) per BTU

T = Temperature (Fahrenheit degrees)

$\dot{W}$ = Mass flow rate, pounds mass per hour

α = Solar absorptivity, dimensionless

ϵ = Infrared emissivity, dimensionless

λ = Rock bed relaxation length, feet

ρ = Density, pounds mass/cubic foot

Subscripts

c = collector

h = house