Excerpt from William A. Shurcliff, "Super solar houses -- Saunders's 100% solar, low-cost designs", pp. 89-118, Brick House Publishing Company, Andover, Mass., (c) 1983 by William A. Shurcliff .

CLIFF HOUSE

Chapter 17

CLIFF HOUSE: A GENERAL OVERVIEW

Cliff House, designed and built *after* Shrewsbury House, has some highly desirable features not found in Shrews- bury House. While approximately equaling Shrewsbury House in being 100% solar heated and having no furnace or wood stove and being almost fully automatic in operation, Cliff House has these advantages:

- It has a very normal appearance-no glass roof.
- It gives the architect an almost free hand in choosing the shape of the house, provided that it has the general form of a rectangular parallelepiped (shoe box), and choosing the layout of the rooms.
- It has independent heating and cooling controls-
- The sunspace is larger and more livable.
- Split-level design is avoided. Entrance to the main story is on-grade.
- One does not have to enter the house via the sunspace .

These features, which may have great appeal not only to prospective owners but also to architects, are discussed in detail in a later section.

A special constraint on the construction of Cliff House is that the actual rate of heat loss must not greatly exceed the nominal (planned) rate. The infiltration rate must be kept very low and the insulation must be installed with care--with no gaps. The margin of safety for achieving 100% solar heating is modest (about 20% for a typical December) and accordingly no gross excess of heat loss can be tolerated. (For Shrewsbury House the margin of safety is larger, about 40%.) Saunders has concluded that, in general, one of the greatest sources of worry to a solar engineer planning for 100% solar heating is uncertainty as to the extent to which the actual rate of heat loss will exceed the nominal (planned) rate. The vagaries of weather are fairly well understood, but the vagaries of vapor barrier and insulation installation are sometimes unpredictable. NOTE: This chapter is written as if the house were complete. This makes the account shorter and simpler. In fact, as of May 1983, some details of construction and solar design were not complete. Some of the facts presented concerning design details are merely my best guesses as to what will become reality. Basic construction of the house and the basic solar design are complete. Therefore, in view of the great novelty and promise of the overall project, it seemed appropriate to include this ac- count although some of the details are not final.

GENERAL DESCRIPTION

Cliff House is situated on a 40-ft.-high, south-facing cliff or ledge in Weston, Massachusetts, about 12 miles west of the center of Boston. A flat lawn ex- tends 40 ft. south of the house, and beyond that the ground falls off steeply. It is a windy location; there are no tall trees to the west or south of the house. It is a 6,000-degree-day (Fahrenheit) location.
This is a two-story, wood-frame, 3- bedroom, 2 1/2-bathroom house with a large integral sunspace on the south and an attached two-car garage on the east. There is an attic, but no basement; ledge rock lies a few feet below the first- story floor.
The living area dimensions are 38 ft. x 28 ft. Thus the floor area of the two- story living region is 2 x 38 x 28 = 2,128 sq. ft. If one adds the 456 sq. ft. area of the 38 ft. x 12 ft. sunspace, one arrives at a total area of 2,584 sq. ft. If one adds also the 624 sq. ft. of the 26 ft. x 24 ft. garage, one arrives at an overall floor area of 3,664 sq. ft.

The house is based on a general design by Edward F. Szabo, an architect residing in Waltham, Massachusetts.

The general shape of the house, the orientation, the exact location, and the solar heating features were specified by N. B. Saunders. Because the solar heating features called for did not involve the living region of the house (except for the provision of two ducts and two fans), the architect enjoyed great freedom in laying out the living region.

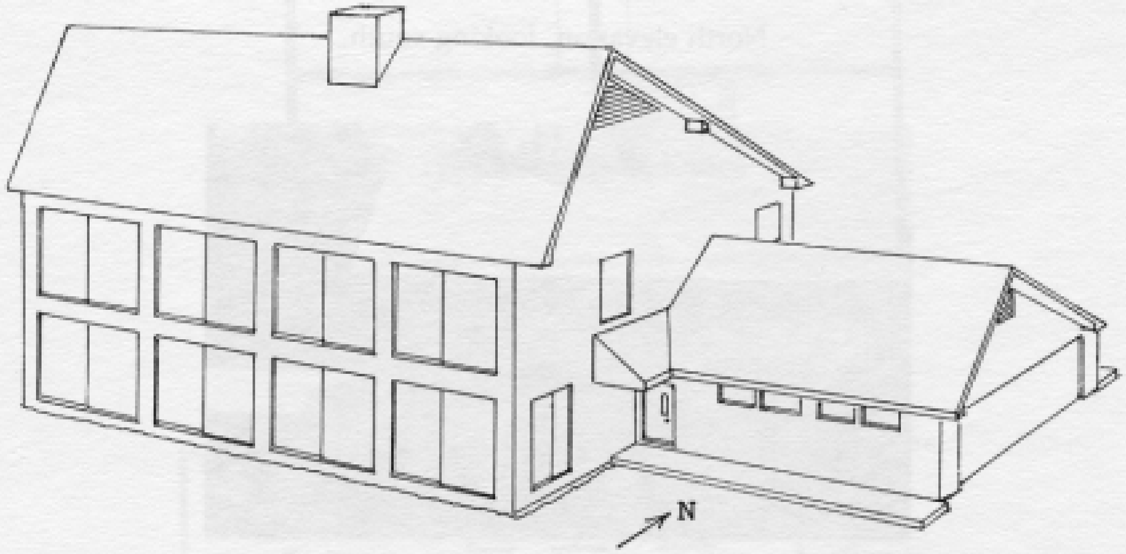
The main solar features include:

- an extremely large glazed area of the vertical south wall of the clerestory sunspace that serves as a solar collector and also a comfortable lounge area
- an upper storage system in the attic
- a lower storage system extending under the entire living region
- a main airflow system
- a solar-heated domestic hot-water system

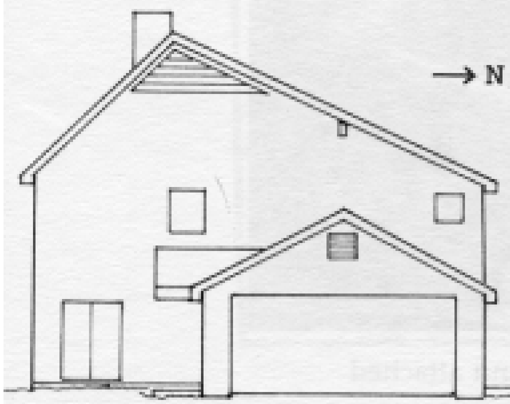
The builder, Antonio Pulsone, is also the owner. He and his family will occupy the house .

The cost, not including land or architect's fee or solar designer's fee, would have been about $120,000 if a typical general contractor had been used. Because the owner served as general contractor, did much of the work himself, and showed much ingenuity in minimizing materials and labor costs, the actual cost is probably considerably less than this.

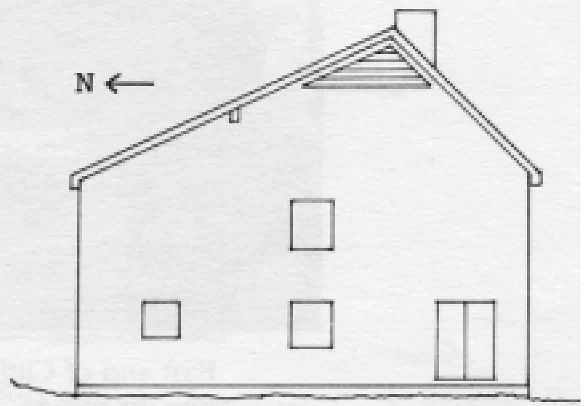
The following drawings show the general layout of the house.



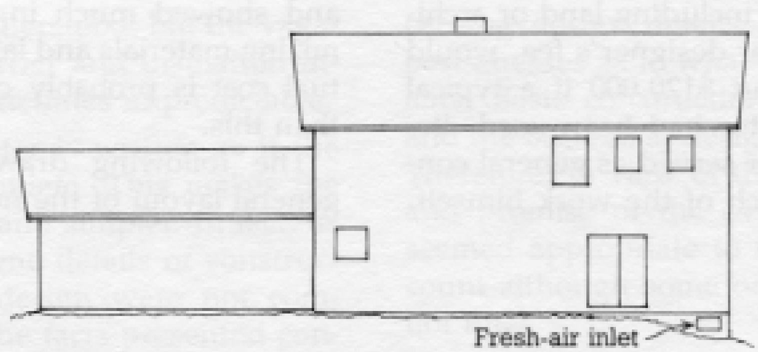
Perspective view of Cliff House, looking northwest.



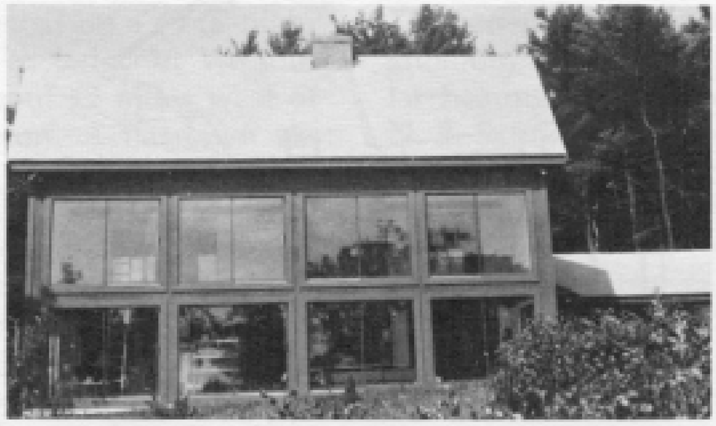
East elevation, looking west.



West elevation, looking east.

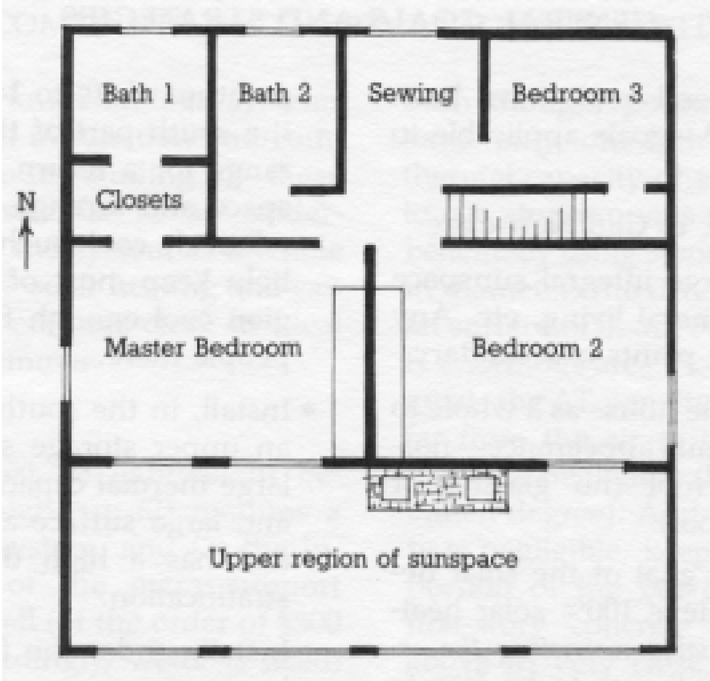


North elevation, looking south.

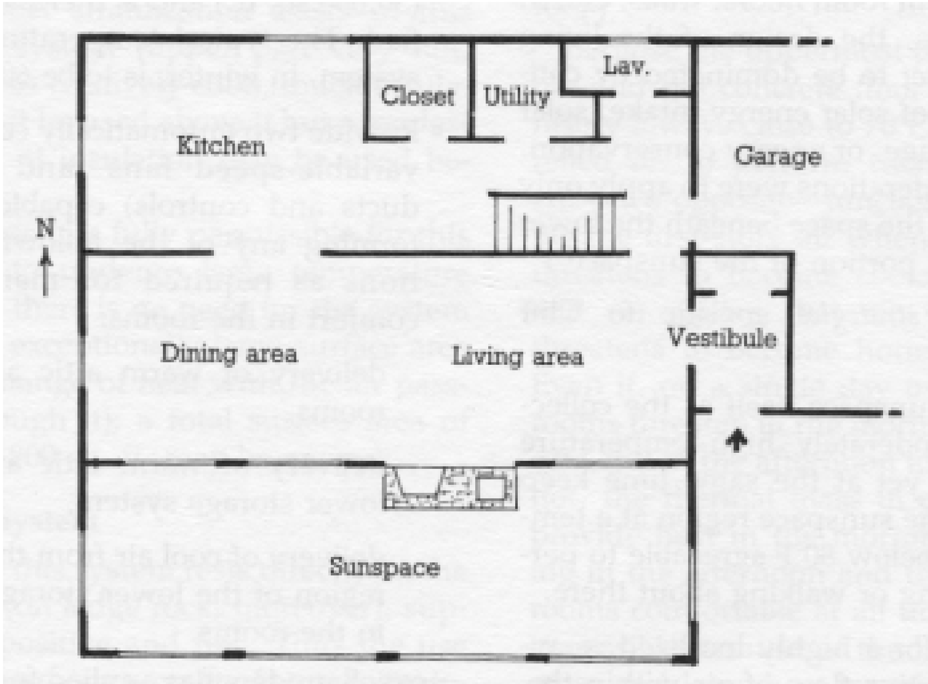


South face of Cliff House sunspace, showing the eight double-glazed windows.

East end of Cliff House and attached two-car garage.



Second-story plan.



First-story plan.

GENERAL GOALS AND STRATEGIES

Many of the general goals have been listed in chapter 3-goals applicable to all three houses.

Some *goals* specific to Cliff House are:

To provide a large integral sunspace for sunning, general living, etc. Any use for growing plants is secondary.

To arrange for the house as a whole to have a very normal appearance-normal-appearing roof (no glazing or panels on the roof) .

A major personal goal of the solar designer was to achieve 100% solar heating *without appreciably restricting the architect.* The architect was to be free to choose the number of rooms, the shapes and sizes of the rooms, the materials used in room floors, walls, etc. In other words, the design of the living areas was *not* to be dominated by considerations of solar energy intake, solar energy storage, or energy conservation. (Such considerations were to apply only to the attic, the space beneath the lower floor, and a portion of the sunspace .)

The main *strategies* specific to Cliff House are:

- Use the sunspace itself as the collector of moderately high-temperature heat and yet at the same time keep most of the sunspace region at a temperature below 80°F agreeable to per- sons sitting or walking about there.
- Arrange for a highly localized, gravity-convective flow of air within the sunspace to carry the collected solar energy (in the form of air at a temperature of 800 to 140°F) upward into the south part of the attic. Also, arrange for a return flow to the sun-space and arrange for this air to be relatively cool (such as 65° to 75°F) to help keep most of the sunspace region cool enough for the comfort of people there.
- Install, in the south part of the attic, an upper storage system that has a large thermal capacity (25,000 Btu/°F) and large surface area (1,800 sq. ft.) and has a high degree of thermal stratification.
- Install, under the first-story floor, a lower storage system that has an even greater thermal capacity (60,000 Btu/°F), a much greater surface area (30,000 sq. ft.) and is thermally stratified. The typical temperature of this system, in winter, is to be 60° to 75°F.
- Provide two automatically controlled, variable-speed fans (and suitable ducts and controls) capable of performing any of the following functions as required for maintaining comfort in the rooms:

    delivery of warm attic air to the rooms,

    delivery of warm attic air to the lower storage system,

    delivery of cool air from the coolest region of the lower storage system to the rooms.

NOTE: Saunders has applied for a patent on airflow control systems having these capabilities.

COMMENTS ON THE TWO STORAGE SYSTEMS

The upper and lower storage systems are very different in function and composition. An understanding of these differences is essential to an understanding of how the system as a whole can provide 100% solar heating and can keep room temperatures close to ideal in winter and summer.

Upper System

This system must be lightweight because (1) it is high up; (2) requires a strong support system; and (3) the incremental cost of the extra support must be kept small (of the order of $500 to $1,000). Accordingly, water is used; it has much greater thermal capacity (Btu's per lb.) than any other low-cost storage material. Because a high degree of thermal stratification exists in this storage system (upper part very hot, lower part relatively cool), much insulation must be used above it but a modest amount of insulation may be used below it.
Because it is fully permissible for this system to undergo large temperature swings, there is no need for the system to have exceptionally large surface area (for exchange of heat with the air passing through it); a total surface area of about 1,800 sq. ft. may be enough.

Lower System

Because this system rests directly on the ground (on ledge rock, moreover), support is positive and free. Thus the use of an enormous weight of storage material-say 100 tons-is permissible. In particular, it is permissible to use stones, even though, pound for pound, they have only one-fifth to one-sixth the thermal capacity of water. The decision to use stones opens the door to a large benefit: by using stones only a few inches in diameter, the designer achieves a total surface of about 30,000 sq. ft.-a truly enormous area. Because the area is so great, the delta-T penalty during heat transfer from the air to the stones (or vice versa) is negligible (less than one Fahrenheit degree). And because this penalty is negligible, keeping the uppermost portion of the bin of stones (and the first-story concrete floor immediately above it) very close to 70°F is feasible irrespective of whether the temperature of the "parent" upper storage system is fairly high (say 130°F) or fairly low (say 85°F).

Because the uppermost portion of the bin and the concrete floor above it are nearly always close to 70°F, they can be relied on to perform two very different-two opposite-functions: (1) *warming* the first-story air whenever that air threatens to become cooler than 70°F, and (2) *cooling* that air whenever it threatens to become hotter than 75°F. Even if, on a single day in winter, the rooms threaten in the morning to be too cold and in the afternoon to become too hot, the thermal mass in question can provide heat in the morning and cooling in the afternoon and thus keep the rooms comfortable at all times. All this is possible because of the large thermal mass and large heat-transfer surface of the bin of stones and the concrete floor.
Clearly, it would be intolerable for the lower storage system to become much hotter than 75°F. It would quickly overheat the lower rooms (by convection and radiation), and the overly hot air here would rise into the second-story rooms, making them too hot.

In summary, the two stories of living space are sandwiched between an upper and a lower storage system, each of which is designed in a special way to perform its special functions. The combination has instant two-way capability: the upper storage system is ready at all times to immediately deliver heat and the lower storage system is ready at all times to oppose *underheating or overheating*.

Note that practically all other solar-heated houses lack this two-way capability. A typical house has only one storage system, and in winter this system is kept hot and so is incapable of preventing room overheating on a warm day in March, say. In summer it is kept cool and so is of no help at all if, on a cold evening in June, the rooms become too cold. The fact is that, in spring and fall, a few hot days may be followed by a few cold days, or vice versa, and many solar-heating systems are incapable of dealing with such a situation. Therefore, a typical solar house needs an auxiliary heating system to handle sudden cold spells and may need an auxiliary cooling system to help out on hot spells. Opening windows is not effective (for cooling) if the outdoor temperature is 90°F.

The design of Cliff House is such that room temperature remains close to the desired temperature even when several hot days are followed by several cold days; and there is no need for the occupant to operate any controls inasmuch as operation is automatic, as explained on page 110. (The occupant must make certain adjustments each fall and each spring; but no day-to-day adjustments are required.)

As explained in later sections, thermal stratification within each storage system is encouraged, i.e., enhanced by the heat-input flow patterns and also by the heat-output flow patterns. The stratification is essential to the overall versatility and efficiency of the temperature control system.

CHAPTER 18

SUNSPACE

The most important and most interesting component of the solar heating system of Cliff House is the large integral sunspace, which itself serves as a solar collector.

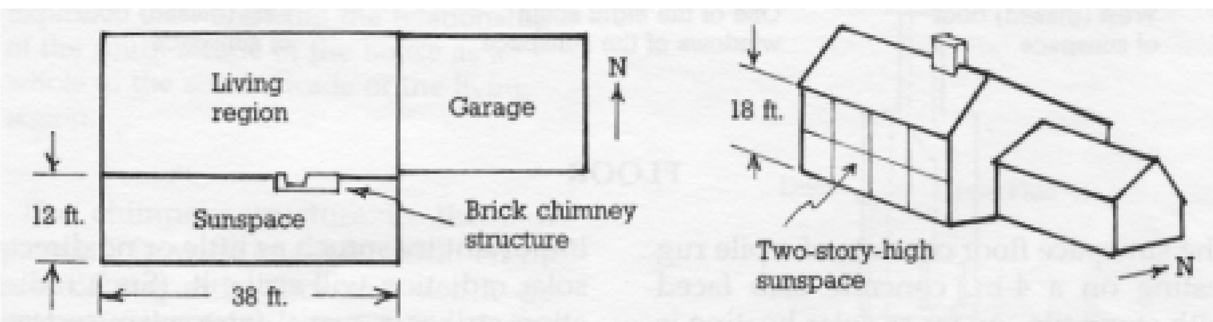
The sunspace is designed to meet these two seemingly incompatible requirements:

- At times when it receives much solar radiation, it must absorb most of the radiation and transfer most of the resulting heat to air within the sun-space. This heated air then flows up- ward to the sunspace ceiling, passes upward through a slot in the ceiling, and streams into and through the upper storage system, situated in the south half of the attic.
- The lower northern portion of the sunspace must at all times remain cool enough (below 80°F) to be comfortable to the people there.

Later paragraphs explain how these apparently incompatible goals are achieved.

OVERALL DIMENSIONS

The sunspace is as long as the house proper, i.e., 38 ft. It is two stories (18 ft.) high, i.e., of clerestory type, and 12 ft. in north-south dimension.



Diagrams showing the dimensions of the integral, south, two-story sunspace.

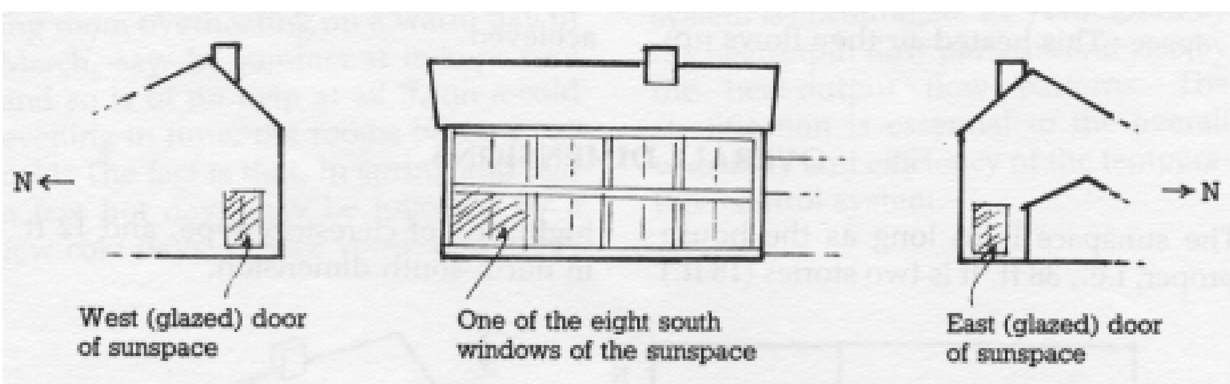
GLAZING

The total area of glazing of the outer walls of the sunspace is 450 sq. ft. This includes:

	Net glazed area (ft.^{2})
south-facing glazing	400
east-facing glazing	25
west-facing glazing	25
Total	450

The south face of the sunspace consists mainly of eight large vertical windows--four in the lower row and four in the upper row. Each of the windows consists of two large panels of glass that are of sliding-door type; that is, they are framed and mounted on rails just as sliding door panels are. However, to eliminate air leakage at the panel edges, the builder intends to seal the panels in shut position. Each of the eight windows is 8 ft. wide by 6 ft. 4 in. high and the total area of the set of eight is 400 sq. ft.

Each panel consists of two sheets of iron-free, water-white, 3/16-in.-thick tempered glass with a 3/8-in. airspace between. The transmittance of each such panel with respect to solar radiation incident within 30° of the normal is 77% . The R-value of the panel is 1.9.
The east door of the sunspace consists of two double-glazed sliding glass panels. Net area: 25 sq. ft. The transmittance and R-value are the same as for the south windows.
The west door of the sunspace is identical to the east door.



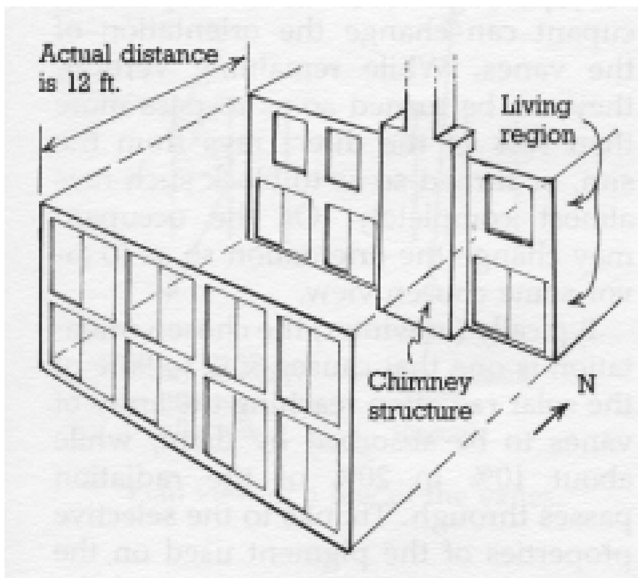
FLOOR

The sunspace floor consists of a pile rug resting on a 4-in. concrete slab faced with stone tile. As far as solar heating is concerned, the color of the tile is not important inasmuch as little or no direct solar radiation will strike it. (Such radiation strikes a *special interception system* discussed in a later section.)

NORTH WALL

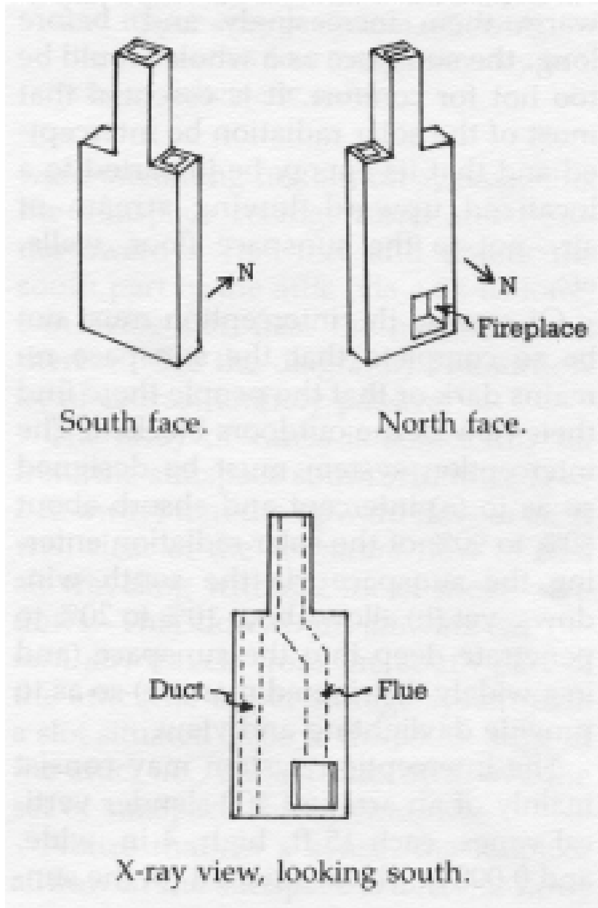
The north wall of the suns pace includes a massive chimney structure and six large glazed areas serving the lower and upper south rooms, providing them with daylight, view, and a little direct solar heating. Each of the six glazed areas consists of sliding glass doors, each of which is double glazed.

The owner may later install, in the north region of the sunspace, a shallow (2 or 3 ft. wide) balcony to serve some of the upper-story south rooms.



Exploded view showing the relationship of the south facade of the house as a whole to the south facade of the living region.

The chimney structure in the sun- space is 8 ft. wide and 3 ft. thick. At the level of the attic floor the width de- creases from 8 ft. to 4 ft. The north face of the chimney structure includes a 3- ft.-wide fireplace serving the 38-ft.long living-dining room. The flue for the fireplace is within the west region of the chimney structure. Within the east portion of the chimney structure there is a 2 ft. x 2 ft. cross section vertical duct. There is no definite plan to use this duct, but it may later be put to trial use to help with cooling, as explained in a later section. Made of ordinary red brick, the chimney structure (not counting the portion within or above the attic) has a mass of about 20,000 lb. and a thermal capacity of about 4,000 Btu/°F.



South face. North face.

X-ray view, looking south.

1
2

INTERCEPTOR SYSTEM

Crucial to the entire collection and storage of solar energy is the interceptor system: a large-area, low-mass system that intercepts most of the solar radiation that enters the sunspace, converts this radiation into heat energy, and promptly transfers the heat to the air. The hot air rises, enters the south region of the attic, and imparts much of its heat to the upper storage system there.

Notice that if any substantial fraction of the solar radiation were to strike the sunspace floor, sunspace north wall, or the brick chimney structure, it would warm them increasingly and, before long, the sunspace as a whole would be too hot for comfort. It is essential that most of the solar radiation be intercepted and that its energy be imparted to a localized upward-flowing stream of air-not to the sunspace floor, walls, etc.

Of course, the interception must not be so complete that the sunspace remains dark or that the people there find their view of the outdoors blocked. The interception system must be designed so as to (a) intercept and absorb about 80% to 90% of the solar radiation entering the sunspace via the south windows, yet (b) allow about 10% to 20% to penetrate deep into the sunspace (and in a widely distributed manner) so as to provide daylighting and view.

The interception system may consist mainly of an array of 400 slender vertical vanes, each 15 ft. high, 4 in. wide, and 0.005 in. thick, situated (in the sunspace) l or 2 ft. north of the sunspace south windows. Normally the vanes are parallel to one another and, often, may be oriented parallel to a vertical north- south plane. Each vane is dark greenish gray in color; a chrome green pigment is used because of its special property of absorbing nearly all of the near infrared portion of the solar spectrum while reflecting a moderately large fraction of the visually important portion (central portion) of the visual-range radiation.

By pulling on a cord, a sunspace occupant can change the orientation of the vanes. While remaining vertical, they can be turned so as to pass more than 95% of the direct rays from the sun, or turned so as to block such rays almost completely. Or the occupant may change the orientation so as to favor some chosen view.

Typically (in winter) the chosen orientation is one that causes 80% to 90% of the solar radiation reaching the array of vanes to be absorbed by them, while about 10% to 20% of the radiation passes through. Thanks to the selective properties of the pigment used on the vanes, the visual transmittance of the array considerably exceeds 10% to 20% ; it may be 20% to 35%, and accordingly the array does not appear dark or gloomy.

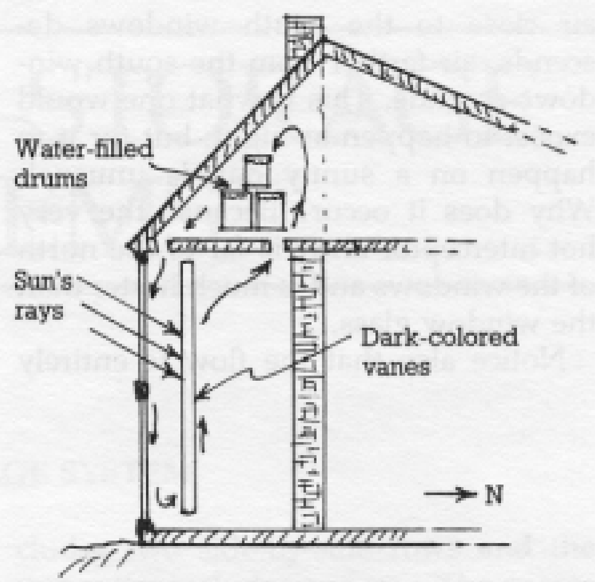
During a sunny noontime in January the vanes receive and absorb much solar radiation, become very hot, and so heat the adjacent air. Result: a strong upward flow of very hot air in the immediate vicinity of the vanes. The upward-streaming hot air, on approaching the sunspace ceiling, turns and flows northward a few feet and enters the south part of the attic (via a 34-ft.-long, 6-in.-wide slot) near the northern limit thereof. (See the diagram.) The airflow is, of course, entirely passive.

The array of vanes is sufficiently far from the sunspace south windows (l or 2 ft. away) that the upward flow of air is well clear of the *downward* flow of cool air traveling within 2 in. of those windows. This downward flowing air *(return* air) travels from the south part of the attic (the upper storage system) via a slot situated close to the south edge of the attic, i.e., almost directly above the set of sunspace south windows.

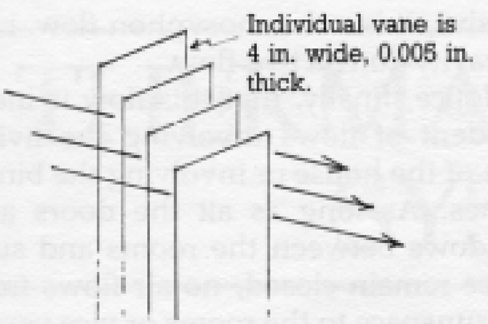
Notice that, in a sense, the looplike airflow in the sunspace is a *reverse* flow: air close to the south windows descends, air farther from the south windows ascends. This is what one would expect to happen at night; but for it to happen on a sunny day is unusual. Why does it occur? Because the very hot interceptor array is far to the north of the windows and is much hotter than the window glass.

Notice also that the flow is entirely passive; it is a thermosyphon flow, i.e., a gravity-convective flow.

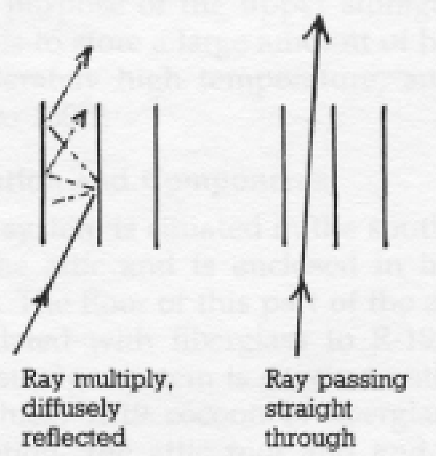
Notice, finally, that this flow is independent of flows involving the living area of the house or involving the bin of stones. As long as all the doors and windows between the rooms and sunspace remain closed, no air flows from the sunspace to the rooms or vice versa.



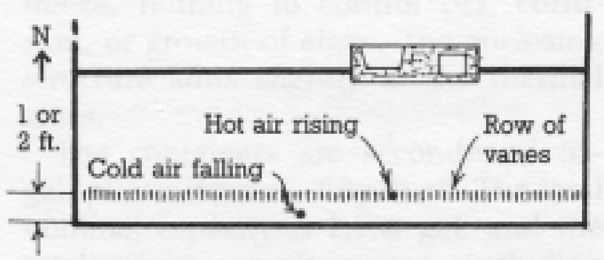
Vertical cross section of the sunspace and upper storage system, showing the paths of airflow on a sunny day in winter. Schematic only.



Perspective view of a few vanes, showing rays passing straight through.



Plan view of a few of the vanes.



Plan view of the sunspace, showing the location of the row of vertical vanes.

CHAPTER 19

THERMAL STORAGE SYSTEMS

UPPER STORAGE SYSTEM

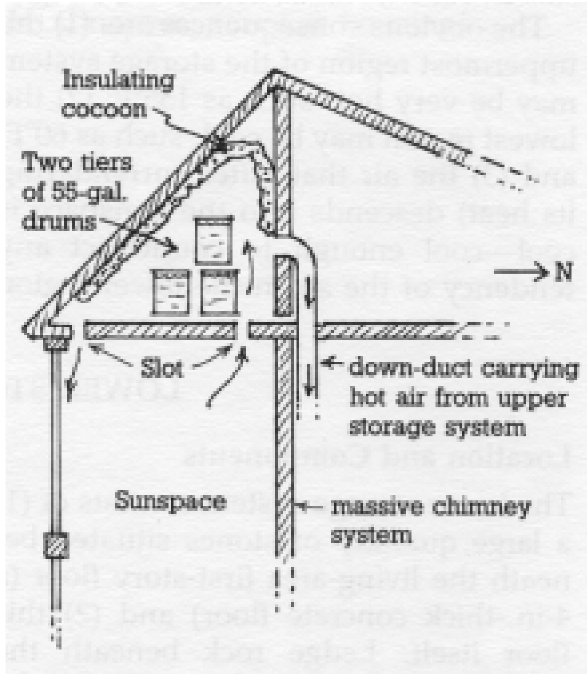
The purpose of the upper storage system is to store a large amount of heat at moderately high temperature, such as 800 to 130°F.

Location and Components

The system is situated in the south part of the attic and is enclosed in insulation. The floor of this part of the attic is insulated with fiberglass to R-19, and the storage system is covered with a 6- in.-thick, R-19 cocoon of fiberglass. In addition, the attic roof and end walls are insulated with fiberglass to R-30.

The system includes 10 tons (20,000 lb.) of ordinary water. There is no anti-freeze, nothing to control pH, corrosion, or growth of algae. The enclosing structure adds slightly to the thermal mass.

The containers are secondhand 55- gal. plastic drums--fifty in all. The total nominal capacity is 2,750 gal. and the total effective surface area, including that of the enclosure, is 1,800 ft.2. The containers are arranged in two tiers: lower and upper. The lower tier includes two side-by-side rows and the upper tier includes one row. The spaces between the drums measure about 2 in.- ample to allow free airflow.



Vertical cross section (looking west) of the south part of the attic and the upper storage system.

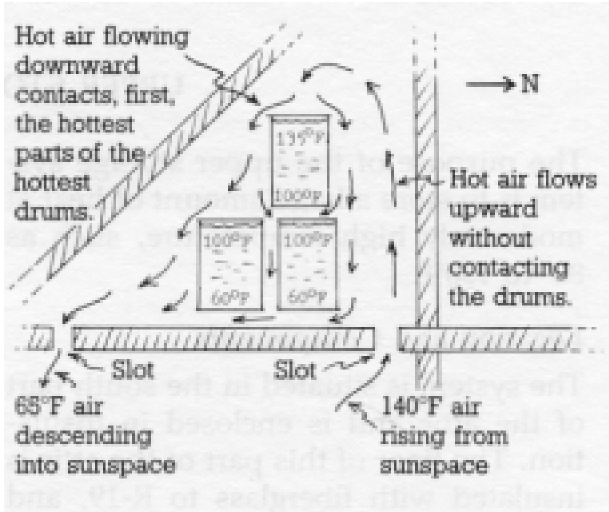
Operation

The hot air from the sunspace enters the upper storage system along such a path that this air makes contact first with the *upper* row of water-filled drums-the hottest ones. After giving up some heat and cooling somewhat, the air descends by gravity convection and contacts the lower rows of drums, delivering heat to them. In other words, the flow path is such as to maintain and even enhance the thermal stratification in this storage system.

Actually, there is an additional way in which the stratification is enhanced: the air contacts the upper portion of each drum before descending and making contact with the lower portion. Thus even the within-drum stratification is enhanced.

The obvious consequences are: (1) the uppermost region of the storage system may be very hot, such as 135°F; (2) the lowest region may be cool, such as 60°F; and (3) the air that (after surrendering its heat) descends into the sunspace is cool--cool enough to counteract any tendency of the air in the lower region of the suns pace (region where people are) to become too hot for comfort.

(As I point out on a later page, the thermal stratification is enhanced not only by the flow path of hot air from the sunspace but also by the flow path of cool air traveling upward via the stair-wells. There are two enhancement processes at work!)



Highly simplified diagram showing how the flow path of the hot air from the sunspace enhances the thermal stratification of the upper storage system.

LOWER STORAGE SYSTEM

Location and components

The lower storage system consists of (1) a large quantity of stones situated beneath the living-area first-story floor (a 4-in.-thick concrete floor), and (2) this floor itself. Ledge rock beneath the stones contributes only very slightly. Plan-view dimensions of the storage system are 37 ft. x 27 ft.

Purpose

The main purpose of the lower storage system is to *regulate* temperature, that is, to keep the temperature of the first-story air close to 70°F-to prevent the temperature from rising much above this on sunny days (when much solar radiation passes clean through the sunspace and enters the living area rooms) or falling much below this on cold nights.

In the short term, the regulation is due mainly to the large thermal capacity of the lower storage system and the concrete floor and also to the large area of the floor. The floor exchanges energy with the rooms by convection and radiation.

In the longer term, the regulation depends in large part on the large heat-transfer area of the quantity of stones. If, for example, the stones threaten to become too cold, they can be heated up fairly quickly by an accelerated flow of warm air from the upper storage sys- tem. They can be heated fairly quickly even if the upper storage system is only moderately hot-thanks to the huge surface area of the stones and the consequent small delta T penalty.

Main features

The 100-ton quantity of stones has a thermal capacity of about 35,000 Btu/°F. This is augmented by the effective thermal capacity of the enclosing foundation walls, underlying ledge rock, etc., with the consequence that the overall effective thermal capacity is about 60,000 Btu/°F.

The effective surface area is about 50,000 sq. ft.

No vapor barrier is used under or above the stones. No moisture problem is expected inasmuch as the house rests on ledge rock, is on a cliff, and the foundation walls are flanked by drainpipes.

Note that no special housing is provided for the stones. The foundation walls themselves, together with the special wall beneath the north edge of the sunspace, serve as housing.

CHAPTER 20

MAIN AIRFLOW SYSTEM

Two forced-airflow circuits serve to distribute hot air from the upper storage system. The two streams start off together: they travel together vertically downward in a l0-ft.-long duct originating at a location immediately to the north of the mid-region of the upper storage system. The flow is forced by the *upper fan* discussed in a later section.

The flow then divides into two delivery paths:

1) first-story delivery path, resulting in delivery of hot air to the first-story rooms
2) sub floor delivery path, resulting in delivery of hot air to the lower-story sub floor space, i.e., to the bin of stones

FUNCTIONS OF THE TWO FORCED-AIRFLOW CIRCUITS

The function of the first-story delivery is obvious enough: the flow of hot air from the upper storage system to the first-story rooms warms these rooms, and the subsequent flow of warm air up the stairwell to the upper story warms the upper-story rooms.

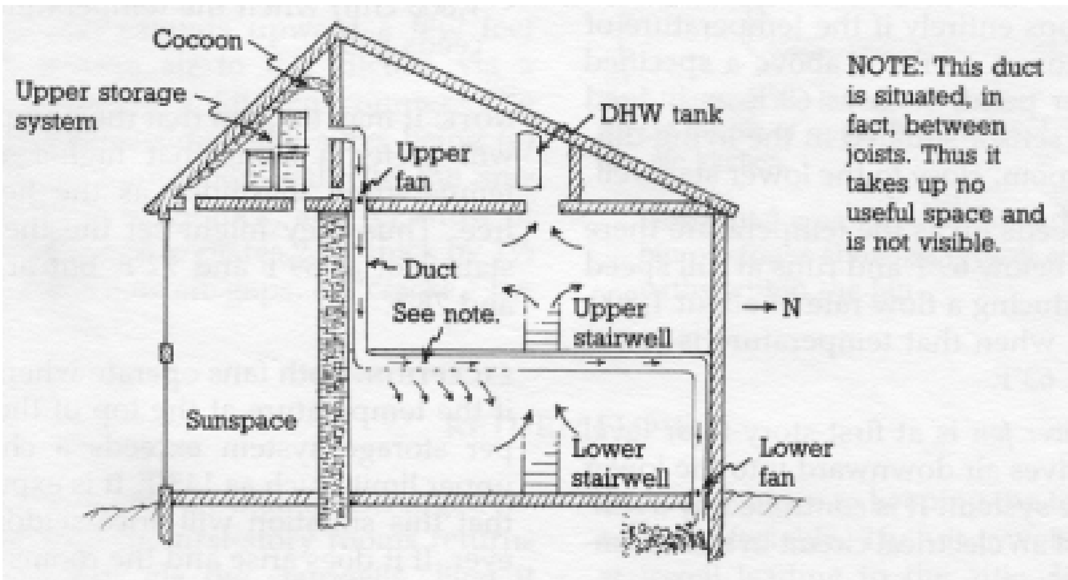
The function of the sub floor delivery is not so obvious. There are, in fact, two functions: (1) to warm the bin of stones, or rather, to warm a large fraction of it, and (2) to *cool* the rooms if they are too warm. How can one flow of hot air perform these two functions? In particular, how can it *cool* a room? It can do all of these things by virtue of the fact that the bin of stones is not thermally homogenous: the part the hot air pervades first (upper central part) is warm, but the part that it encounters last (lower peripheral part) is cool. (The air that enters the bin of stones and then travels laterally and slightly downward tends to become cooler as it travels along.) Thus the process of driving hot air into the warm part of the bin has the consequence of driving cool air out of the cool portion of the bin-and into the first- story rooms. After cooling these rooms, the cool air passes up the lower stairwell and cools the upper-story rooms. In summary, it cools both stories. It re- turns to the attic via the upper stairwell.

THE FLOW PATHS OF DOWNWARD-MOVING AIR

Air leaves the upper storage system at the north side thereof and at a level about two-thirds of the way from the bottom to top of the system. Thus the air is taken from the hotter (i.e., upper) half of the region, but not from the very hottest (uppermost) part. The upper-most part is reserved for extraction of heat by the pipes that preheat the domestic hot water supply.
The air flows vertically downward via a l0-ft.-Iong duct that is 2 ft. x 2 ft. in cross section. Then it turns and starts to flow northward-in two parallel, horizontal, between-joists ducts each of which is 1 ft. x 2 ft. in cross section. It then has two choices of path:

1. It can escape downward into the first- story rooms (living-dining room, etc.)
2. It can flow northward to the north wall of the house and then flow downward into the entrance plenum of the lower storage system. (The flow path within that system is discussed in a later section. Eventually the air emerges into the kitchen.)

The return flows are discussed in a later section.



Vertical cross section, looking west, showing the paths of the main airflow.

Where the warm air from the upper storage system enters the first-story rooms (actually the living-dining room), arrangement has been made for the speed of the air entering the room to be very low. If air moving as fast as 5 ft./ sec. were to strike people there, they would find the air movement very noticeable and unpleasant. But if it is moving at only 1/2 ft./sec., they are unaware of it and experience no discomfort. Accordingly, the designer has provided (within the first-story ceiling) two parallel ducts, 3 ft. apart on centers, and each with a screened opening 14 in. wide and 10 it. long on its underside. Because the total opening is so large, the speed of the air emerging from the opening is only about 0.1 to 1.5 ft/sec., depending on the speeds of the fans. At locations a few feet or more below the ceiling, the speed is much lower: so low that people there are not aware of any air motion.

FANS AND SENSORS

Each fan is rated at 1/4 HP and has variable speed.

The *upper fan* is at attic-floor level and drives air downward. It is controlled by a sensor and an electrical circuit in such manner that:

- It stops entirely if the temperature of the lower rooms is above a specified lower point, such as 69°F, as judged by a sensor situated in the living-din- ing room, close to the lower stairwell-
- It speeds up as the temperature there falls below 69°F and runs at full speed (producing a flow rate of about 1,800 dm) when that temperature is lower than 63°F.

The *lower fan* is at first-story-floor level and drives air downward into the lower storage system. It is controlled by a sensor and an electrical circuit in such manner that:

- It stops entirely if the temperature of the lower rooms is below a specified upper point, such as 72°F, as judged by a second sensor situated close to the first sensor.
- It speeds up as room temperature rises above 72°F and runs at full speed (producing a flow rate of about 1,800 cfm) when the temperature exceeds 80°F.

NOTE: It may happen that the occupants will prefer a somewhat higher room temperature, inasmuch as the heat is free. Thus they might set the thermostats, not at 69°F and 72°F, but at 75°F and 78°F.

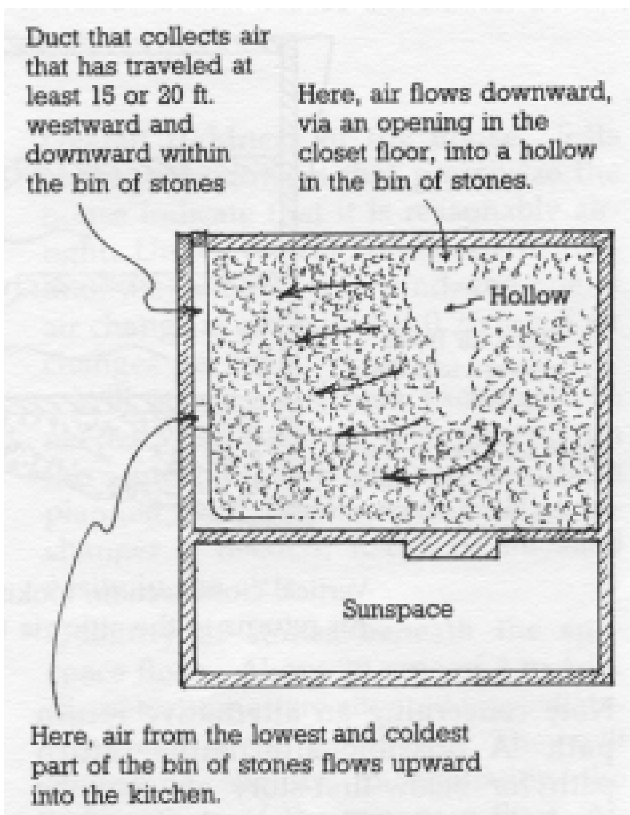
EXCEPTION: Both fans operate when and if the temperature at the top of the upper storage system exceeds a chosen upper limit, such as 145°F. It is expected that this situation will arise seldom, if ever. If it does arise and the rooms then become too hot, the occupants may-to improve comfort-open windows or doors.

FLOW PATH WITHIN BIN OF STONES

When fan-forced warm attic air travels downward and enters the bin of stones, it enters near the center of the north wall of the house via a 4-sq.-ft. opening in the floor of the small closet adjacent to the kitchen. The lower fan is located at this opening, near floor level.

The air first enters an informal inlet plenum, actually a long shallow tongue- shaped hollow in the bin of stones. From here it spreads out in many directions within the bin. While traveling outward from the hollow, it travels slightly downward, losing heat as it goes. Thus the remote, low regions within the bin may remain as cool as 60° or 70°F.

Eventually the air in the bin of stones makes its way to the lower part of the west foundation wall and enters a 27- ft.-long north-south duct. Near the centerpoint of the duct is a branch (an up-duct) that extends upward a few feet and delivers air to the kitchen via a grille beneath a kitchen counter. The duct is three-sided, the sides being (a) the west foundation wall, (b) the surface of the ledge rock, and (c) a row of slanted concrete plates 2 in. thick by 1 1/2 ft. x 2 ft. There are gaps, or "cracks," between plates, and accordingly the duct is "leaky" and serves as a mainfold; air can leak into it (or out of it) along almost its entire length.

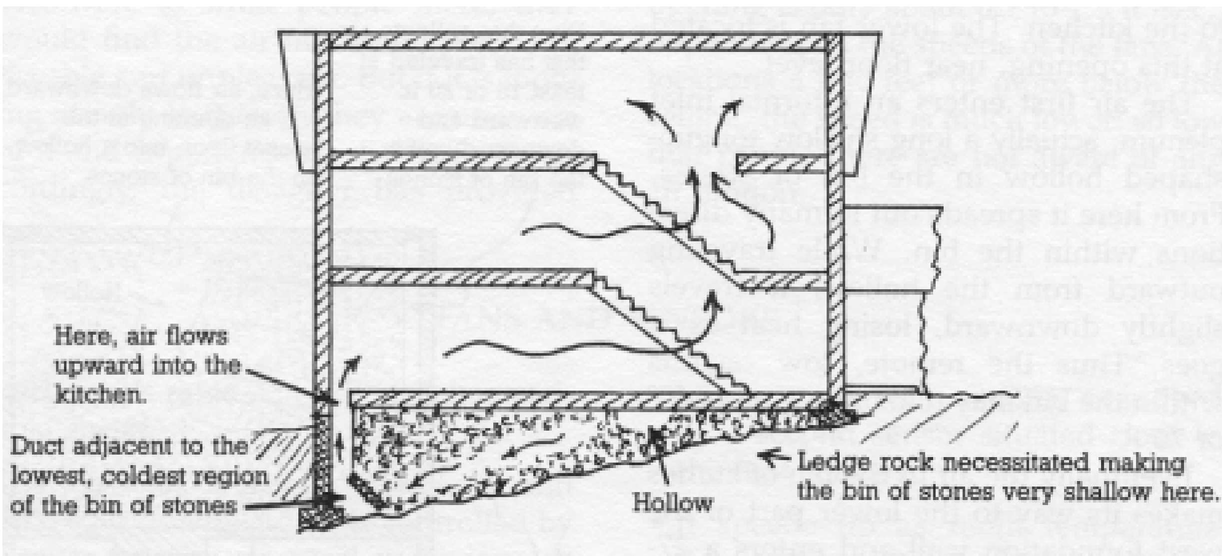


Horizontal cross section through the bin of stones showing typical airflow paths within the bin.

RETURN FLOW

The warm attic air that is discharged directly into the first-story rooms returns to the attic via the stairwells. First it travels up the stairwell leading to the upper story where it spreads laterally and contributes to keeping the temperature comfortable. Then it travels up the stairwell leading to the attic. It enters the south enclosure (the upper storage system proper) via a slot at the base thereof; accordingly, this air, which is relatively cool, encounters first the lowest (coolest) part of the array of water-filled drums, and extracts some heat from this part-thus helping preserve the thermal stratification.

The air that emerges from the bin of stones into the kitchen follows this same general path; it diffuses through the rooms and travels upward via the stairwells and reenters the upper storage system.



Vertical cross section, looking north. Highly schematic. Air returns to the attic via the stairwells.

Note concerning an alternative return path A possible alternative return path for below-first-story air may be used alone or with the path described above. The alternative path would employ (1) a horizontal duct that runs east- ward beneath the first-story floor from the above-mentioned west-foundation- wall duct to the base of the massive chimney structure, and (2) the vertical duct incorporated in the east portion of that chimney structure. For further details, see chapter 2 dealing with cooling the house in summer.

CHAPTER 21

OTHER COMPONENTS

The house has many other interesting components, but they must be described here only briefly.

Vestibule The main entry to the house is via a vestibule that is in the south- west corner of the garage and adjoins the east end of the living-dining room.

Wall insulation Typical walls of the house are insulated to about R-30 with 3 1/2 in. of fiberglass and 2 in. of isocyanurate foam. The walls include a single row of 2 x 4s that are 16 in. apart on centers. The foundation walls are insulated externally with 2 in. of Styrofoam.

East, west, and north windows These have a combined area of 108 sq. ft., or about 5% of the floor area of the living portion of the house. All of these windows have multiple glazing (like that of the corresponding windows of Shrewsbury House) of special type that provides an insulation of R-5.

Vapor barrier All of the external walls, and also the attic roof and gables, are covered with a 0.006 in. polyethylene vapor barrier. In a typical external wall, the vapor barrier is close to the warm side of the wall, being covered there only by gypsum board.

Overall tightness of the house Tests made with blowers that pressurize the house indicate that it is reasonably air- tight. Under typical conditions of outdoor temperature and wind, the rate of air change is estimated at 0.25 to 0.5 air changes per hour.

Will an air-to-air heat exchanger be needed? The answer will depend on the outcome of infiltration-rate tests planned for the spring of 1983. If an exchanger is needed, it can be installed easily in the attic.

Quantity of stones beneath the sunspace floor About 20 tons of 2-to-4-in. diameter stones are situated immediately beneath the sunspace floor. They will contribute slightly to regulating the temperature of the sunspace floor. Although there is an opening (2 ft. x 2 ft.) between this quantity of stones and the much larger quantity in the lower storage system, the 2 ft. x 2 ft. "return port" to the sunspace has been closed; no complete circulatory path is available and accordingly little heat will flow from the lower storage system to the stones beneath the sunspace floor. It is believed that no circulation of air here is needed. (If it is needed, the return port can be opened. Provision has been made for installing a small fan there. If the lower region of the sunspace becomes too hot, the fan could help by delivering air that, on emerging from the sub-floor stones, is at, or slightly below, 70°F.)

DHW system The house domestic hot-water supply is solar-preheated by the hot air in the upper storage system. The 80-gal. DHW tank itself is not in upper storage system space-the south attic space. It is in the separately insulated *central* attic room which, typically, is at about 70°F. The tank is well insulated. The solar preheating occurs in the supply line for that tank; this line, situated within the *south* attic space, includes an initial lower segment situated in air that is only moderately hot, and a final upper segment situated in the hottest air. This latter segment includes a small pre-heat tank (about 40 gal.)

Electric heater At the owner's request, as an added bit of insurance, a 5 kW electric heating element was installed in the attic, at the upper end of the duct that carries hot air downward toward the living-dining room. If for some reason the solar heating system were to fail, this heater could be used to keep the house warm. The expectation is that this heater will not be used.

Vents At each end of the attic is a vent with an effective clear area of 20 sq. ft. In winter the vents are closed with R-40 covers. In summer the east vent will be opened to permit escape of hot air from the sunspace. (See chapter 23 on summertime cooling.)

Port for intake of outdoor air Near the west end of the north foundation wall is a screened, 2 ft. x 2 ft. port that is kept closed in winter but is left open in summer to admit cool outdoor air. A small fan may be installed here to insure fast inflow of cold air at night. (See chapter 23 on summertime cooling.)

Computer calculations In the course of designing the thermal system of Cliff House, and in the course of adjusting and balancing the main parameters, Saunders has made many computer calculations. These give reassurance that the various components will perform about as expected and that, together, they will keep the rooms at about 70°F throughout the winter-even in long, cold, cloudy spells-without the need for auxiliary heat. I do not discuss the computer calculations here, partly because they have not been written up in a formal and understandable manner and partly because many of them were based on various assumptions as to design and construction. Even at this writing (May 1983) some of the design details are still subject to change.

From inspection of some of the calculation procedures, I have learned that they are highly sophisticated. It would be a great mistake for anyone to assume that, because Saunders is very inventive and a great experimenter, his designs are based mainly on intuition, hope, or optimism. Each final design has been evaluated in considerable detail and depth, and embodies much solid engineering.

CHAPTER 22

WINTERTIME PERFORMANCE

Because, at the time of this writing (May 1983), the construction of the house is not quite complete, and the house has not yet been occupied, and there has been no routine operation of the solar heating system, there is little verified information that can be presented on performance.

The goal of 100% solar heating (with help from intrinsic heat) is expected to be achieved. The overall thermal design was aimed at having, in the most difficult month of the year (December), 20% excess of solar energy intake. Some of this excess will be used if the insulation and airtightness do not conform fully to specifications. Another part of the excess will be used up if some midwinter month happens to have, in some year, a climate much more severe than expected. Specifically, it is expected that, in a typical winter, room temperature will seldom be as low as 67°F and perhaps never will be as low as 62°F.

It is expected that, on very cold nights in winter, the sunspace will cool down almost to 32°F. Heat will be imparted to the sunspace, on such nights, by (1) the thermal mass of the sunspace floor and the massive chimney structure, (2) the south faces of the south living rooms, and (3) the warm ceiling of the sunspace-kept warm by the upper storage system. Nevertheless, the sunspace will lose much heat, via its 450 sq. ft. of double-glazed windows on the south, east, and west.

Relative humidity in the living region is expected to remain, in winter, in the range from 20% to 40% .One factor that tends to keep the value low is the fact that the house is situated on a ledge near the top of a cliff; thus the region below the first-story floor is expected to be relatively dry throughout the winter. If the airtightness of the house turns out to be less than expected, the threat of high relative humidity is practically eliminated.

Other performance characteristics worthy of note are:

- The north living rooms are not slighted: they too remain close to 70°F even in long, cold, cloudy periods.
- There are no noticeable air currents in the living region-even when the fans are operating at maximum power.
- There are adequate window areas on all four sides of the house. Daylighting and view are "all around."
- There are no thermal shades to operate each evening and morning. Thanks to the special designs of the east, west, and north windows (R- value approximately 5), persons sitting close to those windows feel fully comfortable.

- Operation is completely automatic. Even if the occupants are away for a week, the sensors and fans continue to do their jobs, adjusting the air flow rates as required to keep the rooms at about 70°F.
- All of the living region has a fully normal appearance. Nowhere in that region is there a Morse (Trombe) wall, or a wall of water-filled containers, or other special solar paraphernalia-
- The domestic hot-water system will be preheated to a considerable extent by stored solar energy. To what extent? Perhaps 80 to 90% .
- The cost of the house (about $120,000) is about the same as that of a conventional house of comparable size. The saving from having no furnace, no oil tank, no furnace room, no radiators, etc., approximately matches the added cost of special insulation, thermal storage, and fans.
- The annual operating cost will be merely the cost of running the fans, estimated at about $100 per year.

CHAPTER 23

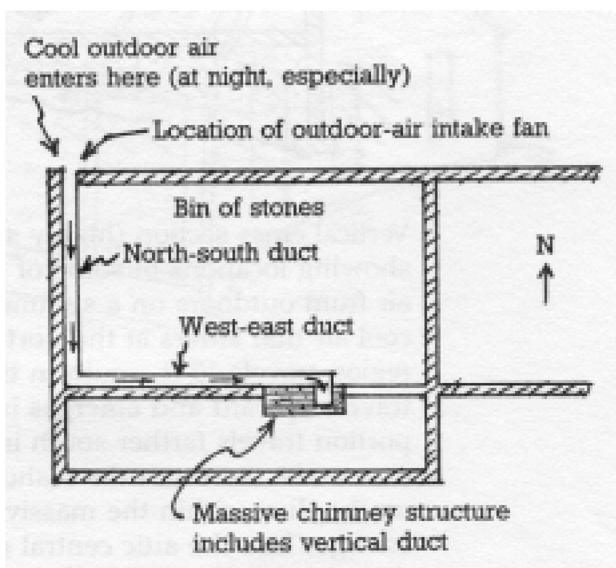
KEEPING COOL IN SUMMER

The problem of keeping the living region of Cliff House cool in summer is made relatively easy by the facts that (1) almost no solar energy enters the living region from the south because of the protection provided by the sunspace, and (2) the house is very well insulated (walls are well insulated, and east, west, and north windows are of special R-5 type).

The lower region of the bin of stones remains at about 70°F or cooler, and the forced flow of air from this region to the rooms keeps them cooler than 78°F at nearly all times.

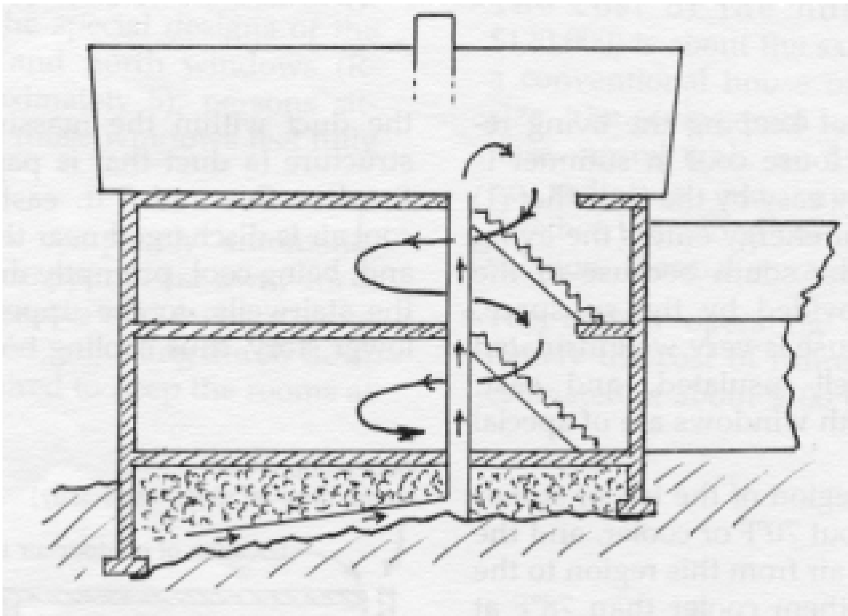
If the bin of stones threatens to become too hot, the occupant can open a port at the north end of the north-south sub floor duct and allow cool night air to enter. A special outdoor-air intake fan, situated at this port, can be used to in- crease the intake of air, a small fraction of which enters the bin of stones directly.

Most of the fan-forced cool air is delivered to the kitchen and to the attic. To reach the attic, the air travels along a west-east sub floor duct and thence up the duct within the massive chimney structure (a duct that is parallel to the fireplace flue and 3 ft. east of it). The cool air is discharged near the attic floor and, being cool, promptly descends, via the stairwells, to the upper story and lower story, thus cooling both stories.



Plan view of the subfloor region of Cliff House, showing the locations of the ducts that carry cool air (on summer nights, for example).

Of course, if the upper storage system threatens to become too hot, the occupants may open one or both of the 20- sq.-ft. vents in the gables. If both vents are open, the prevailing west wind can reduce the temperature rapidly. Because the occupants wish to continue the solar-preheating of the domestic hot water supply, they wish to keep the upper storage system at about 130°F throughout the summer. They may decide to open only one vent, probably the east vent-because (with the prevailing wind coming from the west) the pressure here tends to be slightly negative, facilitating drawing hot air from the sunspace.



Vertical cross section (highly schematic) looking north, showing locations of some of the main paths of flow of cool air from outdoors on a summer night. One portion of the cool air that enters at the northwest corner of the subfloor region travels 15 ft. south in the north-south duct, then travels upward and emerges into the kitchen. Another portion travels farther south in that duct, then travels 24 ft. east in the west-east duct (shown in diagram), then travels up the duct within the massive chimney structure and emerges into the attic central room. Some of this air then descends via the stairwells, cooling the rooms of both stories en route. Another portion, instead of descending, passes to the outdoors via a gable vent. Note: if the occupants open the west door to the sunspace, cool air will enter here also.