by
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ABSTRACT

SOLAR ENERGY AND SHELTER DESIGN by Bruce Anderson

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One of the major contributions to the global environmental crisis is our misuse of energy and our inability to harness certain energy sources. Our country is one of the primary culprits in the crisis, but there are many people who would like to participate in the solution. One means of participating is to develop an active relationship with the natural environment. This thesis will help people to develop that active relationship by helping them to design with solar energy. This will be done primarily through three major sections: 'The Issues', 'Designing with the Sun', and 'Solar Energy Collection and Utilization.'

The first section discusses the environmental situation which requires new attitudes toward living; it discusses those attitudes, especially those which affect our use of the sun's energy; it discusses some of the effects of using the sun's energy.

Section two deals with the misuse of energy by showing energy-economic tradeoffs of various design alternatives which relate to how buildings use the sun's energy. It is shown that by making adjustments in our values (both economic and attitudinal), by making the information which we have about the energy losses of buildings more understandable and usable, we can reduce the heat loss of buildings and reduce the use of mechanical, energy-consumptive devices (especially those which burn fossil fuels).

The third section analyzes our ability to directly harness solar energy (in spite of all of our efforts in section two we may still need mechanical sources of energy). Again, by making adjustments in our values and by better understanding the available information on solar energy collection, storage, and utilization, it is shown that wider application of such energy is practical.

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THE ISSUES 1

<u>THE GLOBAL CRISIS</u> environmental decay, hunger, war, over population, natural resource depletion

> The goal of behavioral processes in a stable system is to achieve an optimum output - never a maximum one. (ED - 3)

1) If the present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years. The most notable result will be a rather sudden and uncontrollable decline in both population and industrial capacity.

2) It is possible to alter these growth trends and to establish a condition of ecological and economic stability that is sustainable far into the future. The state of global equilibrium could be designed so that the basic material needs of each person on earth are satisfied and each person has an equal opportunity to realize his individual potential.

3) If the world's people decide to strive for this second outcome rather than the first, the sooner they begin working to attain it, the greater will be their chances of success.

(LIMITS TO GROWTH - 23)

I do not wish to seem overdramatic; but I can only conclude from information that is available to me as Secretary General, that the members of the United Nations have perhaps ten years left in which to subordinate their ancient quarrels and launch a global partnership to curb the arms race, to improve the human environment, to defuse the population explosion, and to supply the required momentum to development efforts. If such a global partnership is not forged within the next decade, then I very much fear that the problems I have mentioned will have reached such staggering proportions that they will be beyond our capacity to control -

U THANT
1969

Most persons think that a state in order to be happy ought to be large; but even if they are right, they have no idea of what is a large and what (is) a small state....To the size of states there is a limit, as there is to other things, plants, animals, implements; for none of these retain their natural power when they are too large or too small, but they either wholly lose their nature or are spoiled -

ARISTOTLE
322 BC

- Half of the world's production of petroleum to 1970 took place during the '60's. (PC - 5)
- Oil wells are going 30,000' -- previous limits of 15,000' -- more drilling, more energy expenditure, is required per successful well. (SR - 1)
- In 1970, the US used 685 x 10^{15} BTU, 1/3 of all of the energy used in the world. (Ed Allen, MIT, 20 Mar '72)(US is 6% of the world's population and uses 35% of the world's energy -1971) (SFFP - 653)
- The utility industry projects electricity consumption "to double between 1970 and 1980, and almost to quadruple by 1990." (SFFP - 654)
- From 1970 to 2000 the US will use more energy than it used previously, total. (Ed Allen, MIT, 20 Mar '72)
- Energy consumption in 1970 in the US was equivalent to each person having 80 human slaves.(SFFP - 654)
- If we satisfied our power requirements which are projected for 1980, up to 1/3 of all the water in our rivers and lakes would be necessary for cooling. (PC - 5)
- If, by 2000 AD, 75% of our electricity is nuclear generated, we would have a 735,000 megawatt capacity -- at 33% efficiency, that's 30 million pounds of nuclear waste/year.
- With present known global reserves and with the projected rate of growth in the use of those reserves, it is calculated that we have 22 years of natural gas and 20 years of petroleum left. (LTG - 58)
- Residential and commercial lighting, heating, cooking, air conditioning and electrical appliances used 23.2% of the total US energy in 1971. (SFFP -663)
- Space heating consumes nearly 20% of the fuel used in the US.

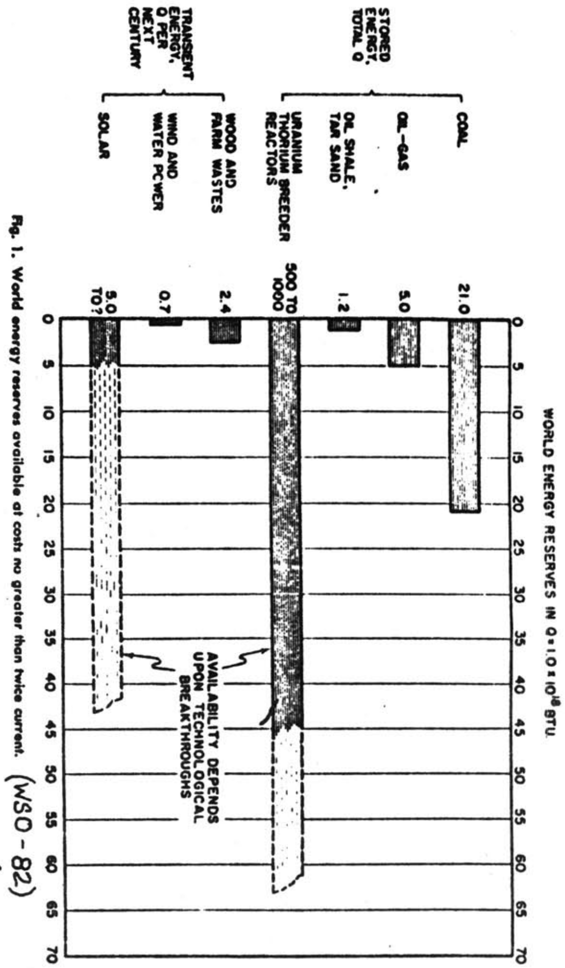


Fig. 1. World energy reserves available at costs no greater than twice current. (WSO-82)

- 420 Btuh/ft^2 (700 cal/cm^2 - day) of solar radiation strikes outside of the earth's atmosphere, the equivalent of 0.7 tons coal/acre - hr. (ETA - 50)
- 330 Btuh/ft^2 reaches sea level through a clear atmosphere, the equivalent of 97 watt-hours, 255,000 foot-pounds, 0.13 hp-hours, 27 mph wind/ft^2 hour, 300 gallons H_2O falling 100 feet, ½ cubic foot of manufactured gas. (FUS - 12)
- Solar radiation is the most abundant form of energy available to man. That which hits 0.5% of our land is more than the total energy needs of the country projected to 2000 AD. (SET - 1088)
- A 33 foot-square roof (100 m^2) can receive in 8 hours on a bright day about 500,000 kcal, the equivalent of 2,000,000 Btu, 150 lbs coal, 15 gallons gas, 58 kw electricity if 10% efficient. (IUSE -2)
- Solar energy could supply half of the 20% of the total US energy consumption that is now used for residential and commercial space conditioning. (SET - 1088)
- Solar space conditioning could be cheaper now than using electricity and could be competitive with the use of gas and oil when they double in price (which they will in a very short time). (SET - 1088)
- Fossil fuels are not optimally used as a source of space conditioning since such work requires much lower temperatures than these fuels optimally produce.
- Low operation temperatures of a solar space conditioning system decrease the possibility of fire.
- A solar energy system doesn't use fossil fuel (a rapidly depleting non-renewable natural resource).
- A solar energy system doesn't pollute (smoke) or produce waste (ashes).
- A solar energy system requires low upkeep costs (but high initial investment).

"It is the predicament of mankind that man can perceive the problematique, yet despite his considerable knowledge and skills, he does not understand the origins, significance, and interrelationships of its many components and thus is unable to devise effective responses. The failure occurs in large part because we continue to examine single items in the problematique without understanding that the whole is more than the sum of its parts, that change in one element means change in others."
(LTG - 11)

A HARMONIOUS RELATIONSHIP WITH PLANET EARTH

The ecological crises of natural resource depletion
high energy consumption
land destruction
pollution
are manifestations of a much larger problem
dis-orientation
discontinuity
insensitivity
of and by human life of and from
a total realization (even partial realization)
of our place as life-creatures in time and space
here and now
Earth, 1973 -
A reliance on the god of technology
the ingenuity of the scientist
the inventor
the confidence in the 'specialist'
the dependence upon the omnipowerful tool - money - to
get us what we need
what we do not need
the lack of global
national
personal self-confidence which we long
previously surrendered to the secular gods -
Man's limited relationship to his environment, both built
and unbuilt
is part of the total problem
dis-orientation
.....
.....
We have great difficulty seeing the grand inter-connect-
edness of our many decisions
indecisions
non-decisions
with the many decisions
indecisions
non-decisions of the world around us.
Building an environment where before there was only the
natural environment is a decision which has far-reaching
effects. Designing that built environment without deeply
considering the macro-
micro-environment around it is sheer idiocy.
When we build, we must have a clear understanding of the
origin of the materials which we use
of the processes by which they came to the site

to thus ultimately become consumed by this built environment.
We should have a clear sense of what the implications are
of the mechanical systems
appliances which we incorporate into this
built environment, in terms of the natural resource consumption and pollution production
which went into their manufacture
which goes into their function
maintenance
in terms of what it means about our
relationship
non-relationship to the natural
environment -
Less technologically developed cultures have used a variety of methods of acknowledging their dependence upon nature:
rituals of supplication
joy
submission
worship
ornaments
jewelry
artifacts
built environments - single houses
great pyramids
spatial arrangements of groups
of buildings -
In many cultures there are, to varying extents, acknowledgement of the power of the sun. Not only does it bring warm relief from cold weather but it burns the very energy out of the body when the warmth becomes instead unbearable heat. Not only does it make the crops grow tall and green, but it scorches them to useless tinder -
As man develops technology
flexes his scientific muscles, he increases his
desire to more
more
more control nature. With regard to the
sun, he wants it when he wants it
at the right temperature
when he wants rain instead he makes it.
Too often he does not understand the meaning of shelter, ambiguously sheltering himself from all of nature's elements simultaneously, with one sweeping effort at enclosure. His awareness of the special qualities of sun-shelter swiftly vanished in the bustle of controlling what he can of the world around him -
The use of solar energy, whether it be for heating
cooling
lighting
or the
generation of electric power, can, with the proper sensitivity to its nature, redevelop within us a deeper understanding of
a closer relationship with both our built environment and our unbuilt, natural environment. Such an understanding might be only a piece of the total process of redeveloping a total ecological understanding of a harmonious relationship with our home
planet Earth -

A flat-plate solar heat collector embodies an element which must be given a great deal of consideration when choosing materials. This element is the collecting surface, which in many cases has been made of aluminum and coated with flat-black paint (the MIT solar house IV used two coats). The water-circulation pipes through which the heat is conducted from the aluminum to the water have often been of copper. Both aluminum and copper are among two of the non-renewable natural resources which are in very short supply.

At our present rate of usage and with our present known reserves, aluminum is due to last 100 years and copper 36 years. At our present exponential rate of growth of usage (we use more and more each year), the present reserves would last only 31 years and 21 years respectively. Should we discover five times more of these precious metals than we now know about (being optimistic!), those numbers become 55 years for aluminum and 48 for copper. (LTG - 56)

Since the collection of solar heat is part of an effort to live more in harmony with our home, planet Earth, every effort should be taken in the design of the system to respond to that attitude. The ecological tradeoffs (in this case possible higher efficiencies with aluminum and copper against lower efficiencies using renewable natural resources) must be weighed taking many considerations into account.

For example, if efficiency is decreased by using alternatives to aluminum and copper) is it significant enough so that a larger collector must be built, thereby using more of some other natural resource (which we hope would be renewable)? Or if a larger collector is not built, does the auxiliary heating system (which would have to satisfy a larger percentage of the heating load)run on precious fuels (oil or gas) which are also non-renewable and in very short supply?

What are the consequences on the depletion of non-renewable natural resources of using alternative materials? For example, plastic pipe is used instead of copper. Plastic may be either wood- or petroleum-based. With proper management, wood is a renewable natural resource, but many petroleum-based plastics might be considered as a poor alternative to copper, depending on the amount of petroleum used, the manufacturing process (water-use, energy-use, and pollution resulting from manufacture), and life-expectancy of the product (use of short-lived products is generally ecologically-poor practice).

Asphalt may have an absorptivity as high as 97% (this needs to be checked); the aluminum-copper tube assembly of the MIT House IV had the same. Metals other than aluminum are being investigated for absorptivity when coated with black paint. It may be found that the main advantage to aluminum is its light weight.

SOCIAL IMPLICATIONS of increased house cost

There are several social implications due to the higher initial cost of a solar space conditioning installation. Already the sale price of houses is so high that a very large percentage of our population is unable to afford them. They are unable to make a down payment and to pay high monthly mortgage payments. Many efforts are being made in the building industry to control costs, but prices continue to rise, as much as 45% in five years. It has been suggested that one way to decrease initial cost is to encourage the utility companies to own the mechanical equipment of the house (decreasing the initial cost) and to then rent it to the homeowner. A similar means might be used to lessen the financial burden of a solar space conditioning system. Perhaps there should be government tax incentives to encourage its use, taxing heavily homes which use fossil fuels (including electricity which is generated by fossil fuels) and which pollute the air as they heat the house, or giving tax breaks to those who use solar heating.

Community and collective approaches to housing can also ease the financial burden through a sharing of land, space, and utilities. Exploration should be made into the economic desirability of large community collectors and storage systems. The collector, for example, might help to shelter a community activity. Perhaps a community activity or factory could make use of the collected heat during the spring and fall when it is not needed for space conditioning (for example, a

This is difficult to intuitively believe, however, since it seems advantageous for both the collector and storage to be contiguous to the space they are heating so that some of the inefficiency of the system due to heat loss will be regained by capturing some of that loss in those heated spaces. However, this possibility is explored in section three, 'Long-term Storage'.

community swimming pool). If each house had its own collector, perhaps the excess heat collected by them during the spring and fall could be given to the community in exchange for auxiliary heating from a centralized source during the winter.

POLITICAL RAMIFICATIONS

Listed to the left are companies who make things for the home - and who make war products ....

The introduction of solar energy use in this country on a large scale is as much a political issue as it is an ecological one. The large energy-producing and -consuming corporations of this country have powerful voices in our federal legislative and administrative halls. Pollution control laws and repeals of resource depletion allowances, for example, are fought bitterly by this group. The federal government should consider laws aimed at all levels of energy consumption to discourage the use of fossil fuels and encourage the use of alternatives such as solar energy. HUD could be a leader in this, not giving FHA loans to energy-wasteful housing designs, or giving lower interest rates to those which use alternatives such as solar energy. Solar collection devices could be freed from property taxes.

I. Companies Who Make War Products--Who Make Things for the Home

ALUMINUM CO. OF AMERICA Wear-ever utensils, Alcoa wrap, Cutco cutlery. Also: 2.75 inch rocket motor tubes.

AMF INC. Voit rubber, sporting goods, Harley-Davidson motorcycles. Also: Mk 82 bomb parts and metal parts for 750 lb. bombs.

BULOVA WATCH CO. Watches. Also: fuses for rockets and anti-personnel projectiles, including the 50 mm white phosphorous projectile. White phosphorous ignites on contact with the air and continues to burn even when imbedded in flesh.

E.I. duPONT deNEMOURS AND CO. Teflon, Cantrece, Orlon, Mylar, Dacron, Lycra and Duco. Also: TNT, rocket propellents, dynamite.

EASTMAN KODAK CO. Cameras, film, office supplies and copiers. Also: multi-million dollar contracts for various explosives.

FORD MOTOR CO. Philco, Ford and Autolite. Also: Shillelagh missile systems, systems for Chaparral missile, electronics equipment.

GENERAL ELECTRIC CO. Refrigerators, washers, dryers, stereos, etc. Also: Mk 73 Tartar missiles, Chaparral missile guidance, guidance and control systems for Polaris and Mk 3 Poseidon missiles.

GENERAL MOTORS CORP. Frigidaire, autos and auto parts. Also: M 16 weapons, Mk 48 torpedo warheads, 81 mm projectiles, parts for 105 mm projectiles, 155 mm self-propelled Howitzers.

HONEYWELL INC. Computors, Pentax, Rollei and Elmo photographic equipment, and thermostats. Also: Minutemen III components, Mark 46 torpedoes, Rockeye II cluster bombs, white phosphorous anti-personnel mines, and guava bombs. A "mother" bomb contains hundreds of guava bombs, each of which release in turn 300 steel balls, which explode, filling the air with a deadly hail.

INTERNATIONAL TELEPHONE AND TELEGRAPH CO. Owns Continental Baking which makes Wonderbread, Hostess Cupcakes and Morton Foods and owns Avis. Also makes: electronic counter-measure equipment.

MOTOROLA INC. Stereos, radios, TV, tape recorders. Also: 40 mm shell fuses, bomb proximity fuses.

RAYTHEON CO. Refrigerators, air conditioners, gas stoves, electronic tubes. Also: Chaparral missile systems, engineering for Hawk missiles, control systems for Sidewinder missile, advanced development for SAM-D missile.

RCA CORP. TV, radio, stereos, records, Hertz, NBC, Whirlpool, Random House, Modern Library, Pantheon, Knopf. Also: Fuses for Zuni rockets, development of Advanced Surface Missile.

SINGER CO. Sewing machines, vacuums, record players, furniture. Also: Modification of Mk 48 torpedo, instrument dev. Advanced Ballistic Re-entry system, guidance for Poseidon missile.

II. Other Companies with Major War Contracts

ASIATIC PETROL Indirectly related to Shell Oil Co.

AVCO CORP. Paul Revere Life Insurance, Seaboard Finance Co., Carte Blanche Corp.

GENERAL DYNAMICS CORP. Associated Finance Corp., Strombert-Carlson Corp.

GENERAL TELEPHONE AND ELECTRONICS CORP. Sylvania radios, lights, TV's, telephones.

GENERAL TIRE & RUBBER CO. Ohio-tires, tubes, rubber products, Pennsylv. Champion tennis balls, RKO-General, Inc.

IBM Typewriters, etc.

KAISER INDUSTRIES Aluminum products, Willy Jeeps.

LING-TEMCO-VAUGHT, INC. Wilson sporting goods, University loudspeakers, Braniff Airways.

LITTON INDUSTRIES Stouffer Foods, Cole Steel Equipment, American Book Co., Van Nostrand Pubs., Royal Typewriters.

MAGNAVOX Electrical entertainment equipment, band instruments, Consolidated Furniture Industries.

MOBIL OIL All Mobil products.

NORRIS INDUSTRIES Waste King gas and electric ranges, ovens, dishwashers, space and water heaters, garbage disposals.

OLIN CORP. Pool chemicals, insecticides, fertilizers, Winchester firearms.

PAN AM WORLD AIRWAYS All Pan-Am lines, Intercontinental Hotel Corp., Grandes Hotels, New York Airways.

SPERRY RAND CORP. Health and beauty care products, Remington shavers and typewriters.

STANDARD OIL Chevron, Standard, Humble Oil and

(PYP-22)

THIRD WORLD ISSUES

Introduction of the use of solar energy into third world countries is as complicated a problem as is its introduction into the countries of higher-energy use. As third world countries increase their energy demands and raise their standards of living, they may see solar energy introduction as a ploy for Western countries being able to hoard for themselves the diminishing supply of fossil fuels. If we should be able to get around this issue, there are others:

> These countries generally are in the warm belt of the world and need cooling mechanisms more than they need those for heating. The technology for using solar energy for cooling has yet to be developed at an unsophisticated level applicable for use in 'underdeveloped' countries.
>
> Even if solar cooling devices were properly developed, the demand for solar devices would more probably be for those which could pump water for irrigation, refrigerate food to improve diets, or generate electricity.
>
> Appropriate solar devices should require little, preferably no, auxiliary electricity for their operation. They could permit moderate and simple use of auxiliary fuel (which is usually very expensive in third world countries). They should be a very low initial cost and should take into account the use of local materials (many countries do not manufacture glass, or aluminum, or copper....) Cheap and plentiful labor might be available for unskilled construction and daily manual adjustment or the orientation and tilt angle of solar collectors.

The appraisal of 'need' in such countries is difficult ... Do aborigines 'need' radioes? hot water? This appraisal is the most important and difficult part of almost any aid to other countries, and the introduction of solar energy utilization is no exception. (No answers are given here).

The architectural significance of the integration of ecological technologies into built form lie far deeper than trying to synthesize, for example, a huge solar heat collector and concomitant huge storage tank into an architectural whole, or in trying to use alternative ecological mechanical accessories, for example, low-waste-producing toilets. Inextricably interwoven into the broader understanding of the interrelationship between ecology and architectural design is an awareness of man-nature-man-nature... (If in fact we dare even to be bold enough to semantically separate man and nature).

An intense awareness/understanding/sensitivity to this man-nature interaction is in fact a requisite foundation for making a contribution to this interaction through the application of ecological principles to built form. Since the advent of homo sapia, individuals and groups have searched for, and to various measure have succeeded in discovering, man's role as a member of earth's living community. Art and architecture have released some of the most sensitive conclusions to this search, and the man-nature synthesis potentially evolves to higher heights with each such contribution.

It is no secret however that our technology has and is designed for the most part to exploit the abundance and generosity of this planet, but we have the beginnings of a 'rebirth of wonder', as well as the technological capability to truly act and interact with nature in a positive, contributory way. Such a contribution requires an intense awareness/understanding/sensitivity to the man-nature interaction. Man is at a crucial point in his history: he can synthesize technology and nature, but not without this sensitivity.

INTEGRATION OF SOLAR ENERGY with other life functions

Too many solar researchers have seen the use of solar energy in the very narrow context of simply replacing the existing job of fossil fuels without investigating what other changes might be necessary in other facets of ourlives which are in some way affected by the global energy crisis. Solar energy collectors are tacked onto a house which is designed in such a way as to be sold to a 'contemporary' or 'modern' buying public. The dwelling may have extra insulation, heavy curtains across the windows, or even triple glazing, but the owner is not in other ways aware that his heat comes from the sun. Engineers and scientists, in developing solar systems, have just assumed that 'you can't change human nature' (in what other countries is there such an expression?) and have tried to design systems which require little or no owner participation in its performance. The results have often been complicated control systems which break down, add to the cost, and make only small gains in overall efficiency (when they are working).

Human nature may have to change, however. We are coming to a point in human history in which the change must come, either willingly of our own volition or forcefully through a series of traumatic, perhaps catastrophic global happenings (fuel shortages, starvation, pollution deaths). Even if the latter possibility is overdramatic, it should be clear that we should, when dealing with solar energy, look beyond simply tacking a collector onto a house, and judging its success on its fossil fuel savings. One of the primary changes will be in the attitude of people toward consumption - The per capita consumption of energy and natural resources in this country is about fifty times greater than that in India. People may decide that such exorbitance is unjustified. As this affects the design of their home/shelter, efforts will be made to use less energy and resources in its construction, in its maintenance, and in its functions. To decrease consumption of fuels and other natural resources for the purposes of heating and cooling the home/shelter, large efforts will be made to design the house in a way that it will lose less heat through its skin to the outside during the winter (but gain as much of the sun's energy as possible), and gain less heat through its skin from the outside during the summer.

Most locations in the world need, in addition to taking proper advantage of the natural processes of heating and cooling, auxiliary man-made systems. Such systems range from simple hand-fed fires to complicated, automatically-controlled mechanical heating-cooling-ventilating-humidifying-air purifying-systems. The latter systems are often needed, in hospitals for example, but too often we have ignored the free contributions which nature can make to our comfort; we have taken advantage of our cheap sources of energy (and assumed that they are inexhaustible); and we have completely, or as much as possible, isolated our buildings from the outside, introducing technological, resource-consuming devices to regulate the inside weather (often leaving no control to the actual users).

Thus as one change will be the attitude toward consumption, another will be a change in how we deal with the interface between the home/shelter and nature. We will recognize that our natural resources are not inexhaustible, that our cheap sources of energy will become expensive, that we must take advantage of some of nature's gifts to our heating, cooling, ventilating needs.

It may follow from these two mentioned changes that in cases where technological solutions no longer make sense, owner/user participation may be necessary to take better advantage of what nature has to offer us. This in fact may be another change which we may make -- that instead of relying on other people (for example, builders and repairmen) and on technological devices (from electric toothbrushes to fully automated indoor climate controls), we will, to a much greater extent, participate in and interact with the life functions which support our existence.

Let us assume that we intend to collect and store the sun's energy and use it for heating or cooling the house or for heating domestic hot water. In subsequent pages it will be shown that there are numerous problems with making such a system work. As has already been mentioned, one of the setbacks of earlier systems has been the method of incorporating them into the total scene of domestic living, that is, the systems were simply tacked onto existing types of shelters and existing attitudes and patterns of living. Little attempt was made to incorporate them, to integrate them into other life functions. When we try to solve problems by making significant innovative change, it is often advantageous to investigate other areas within the total context of the problem and the solution. Slight changes and adjustments in other areas might lead to a more harmonious solution than the one originally conceived.

Thus when we find that the use of solar energy may be a viable alternative to present methods of heating and cooling, perhaps, by looking at some of the many other life functions by which we are affected, we can more readily integrate a solar energy system into the home/shelter situation and come up with a better solution. This thesis deals with some of those other life functions, particularly those which are related to the heat loss and heat gain of the home/shelter. It has been suggested earlier that a method of solving the solar energy problem might be to look at the community level of collection and distribution. But there is another important area of investigation which could lead to better solutions: just how can all of the life functions work together in such a way so that the inefficiencies of some will be balanced by the efficiencies of others? Or, another way, is it possible for the total set of life functions to operate more efficiently (using less energy) if they were more integrated with each other?

There are many scales at which to direct research into such an integration of functions. An example at a very large scale is the economic advantage that seems to be derived from using the heat generated by the insides of a building to help balance the heat loss at the exterior skin of that building. At an even larger scale, warmed cooling water from electric power generators is being distributed to homes for heating purposes.

At the level of domestic solar energy use, it will be shown that an auxiliary heating system is necessary for those times when there is not enough sunshine or when the heating demand is too great. Perhaps instead of the usual investment in a furnace, a combination of heat pumps, windmills, waterwheels, fireplaces, space heaters, heat from a compost pile, or the burning of homemade methane gas would work better (use less fossil fuels). Perhaps instead of the solar energy system being limited to use for winter heating, it could also be used for cooling during the summer, for heating domestic hot water, for cooking, for growing food year round, for the distillation of water, for the generation of electricity, and so on, thus spreading the cost of the system over a large number of functions. Such avenues of integration are only offered as areas of possible investigation and will not be discussed in detail. But it is up to the people involved in a project utilizing solar energy to investigate these possibilities. The following is one such integration of life functions, diagrammed by Duane Huntington and Jiri Skopek in "Artificial Domestic Ecosystem", a booklet which they wrote in 1972.

The use of integrated systems on a self-sufficient level requires an intense evaluation of each case. 'No man is an island' is especially true ecologically. There is no question that animals vary in the extent to which they depend upon their herd, hive, pack, flock, or other such kin group. Within the single species, "man", the variation is just as great, with different degrees of success at independence and self-sufficiency.

A single building or group of buildings which is trying to respond ecologically to the environment may have much greater success if it makes the effort in conjunction with others. Fuller has said that

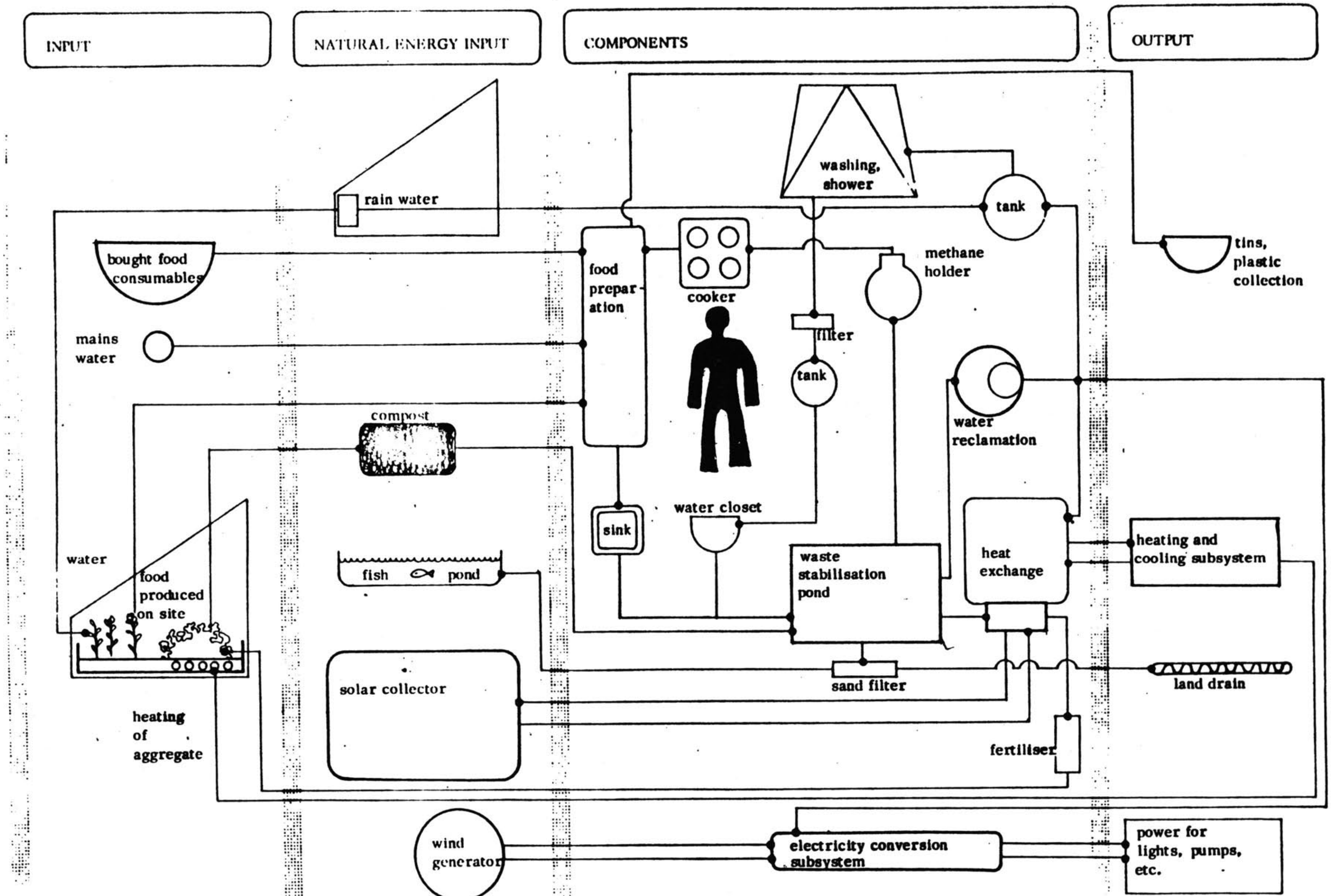


FIG. 9 - DIAGRAM OF INTEGRATION OF SUBSYSTEMS AND COMPONENTS

FROM "ARTIFICIAL DOMESTIC ECOSYSTEM"

ownership of property and things is 'immoral' in these times of limited resources. So too, it may be immoral if each 'island' is equipped with everything it needs to maintain self-sufficiency. It is necessary to evaluate in very broad terms the relative efficiencies of various degrees of self-sufficiency, efficiency not only in terms of personal comfort, but also in terms of consumption of natural resources and energy.

For example, at present, the domestic sector of our society accounts for about 35% of the energy commercially consumed in this country. If, through the introduction of 'total energy systems', integrated ecologically-technical systems and the like (making the dwelling self-sufficient and using few natural resources in its function and maintenance), we were able to decrease this amount to 10%, would we really be making progress in lowering the energy and natural resource consumption of the country as a whole if the resulting situation required that the 25% change in energy consumption by the dwellings was merely transferred to the industrial complex which was being required to produce the many individual mechanical subsystems? We would think not (but we don't know for sure), but such are the questions and issues which we must continually raise as we deal with the question of solar energy.

OVERVIEW OF DESIGN PROBLEMS

Let us abandon the self-mutilation which has been our way and give expression to the potential harmony of man-nature. The world is abundant, we require only a deference born of understanding to fulfil man's promise. Man is that unique conscious creature who can perceive and express. He must become the steward of the biosphere. To do this he must design with nature -

Ian McHarg
(DWN - 5)

We must set a tone and adopt an attitude which will aid us in approaching the discussion of energy-economic tradeoffs.

your shelter

There are a number of reasons for the use of the word shelter instead of the traditional words: home, house, or building. It is one of the main premises of this thesis that one way of making solar energy collection and utilization more practical is by changing our lifestyle, either slightly or drastically. The use of the words house and home may carry connotations too strong to overcome.

The traditional method of collection and utilization of solar energy is to assume that 'people never change' and that the only way to sell the use of solar energy to the public is to make it appear to the homeowner that everything in life is as it always was; he should hardly be aware that he is using solar energy. Such a situation seems

... We talk a lot these days about the ecological revolution, about new life-styles, and about new priorities but we tend to think more in terms of new versions of old mistakes - safer detergents, cleaner-burning automobile engines; that sort of thing. I don't see that very many of us are committed to any real change, and that's a shame because those who have tried to simplify their lives - and I count myself as only one of the most timid among them - seem to share a unanimous and very genuine real connection that real riches - the kind Thoreau was talking about - increase in direct proportion to the simplicity of one's life -

Malcolm Wells
(AES - 434)

almost impossible. For anyone using solar energy, looking for the sun is going to be first on each day's agenda. Such a person is also going to go to great lengths to utilize the sun's energy as wisely as possible. Thus, using solar enrgy requires new attitudes toward the sun, new attitudes toward the conservation and utilization of energy, and new attitudes toward home-house-shelter design.

The use of the word shelter also implies that we are 'sheltering' something from something else. Such is the case. We are making an effort, when designing and constructing a shelter, to protect ourselves and our activities from forces which may affect us and these activities in ways we may not like. (Designs also seek to do other things of course, such as to enhance the performance of the activities and to promote sense of place and time). People are protecting themselves according to their individual needs (cooking, sleeping, sewing, reading, boatbuilding, etc.), according to their site (animals, vegetation, terrain, wind, other people) and according to the climate (it would thus seem obvious that houses in northern climates would be different from those of southern climates; this is often not the case). By using the word shelter, it is hoped that a person can, before incorporating the use of solar energy into his structure, define in greater detail his activities and how they relate to and interact with each other, define what the forces are that affect those activities and how to protect and shelter himself from those forces. If a person is making or has made the above analysis, then he may perhaps be ready to take the next step of incorporating ecological principles into the design. He may want to take the further step of collecting and utilizing solar energy.

ecological principles - the site

A person has not satisfactorily analyzed the solution for the sheltering of his life's activities unless he has seriously considered the solution in the context of the site. A site must be examined as an element of a much larger order, the earth's BIOSPHERE. The discussion of the global crisis at the beginning of this thesis began to examine this relationship. The site, the land of which a person is steward, cannot be made into an island of itself, except figuratively, becoming highly self-sufficient, or literally, surrounded by water or walls. But the survival of the land is dependent upon its interaction with the entire biosphere.

A lot of words have been written about how the biosphere, the site, and the shelter respond to and inter-relate with each other. It is becoming clearer that one of the primary roles of the intelligent animal, homo sapiens, is the intelligent stewardship of this planet. More direct use of the sun's energy (such as solar energy collection and utilization, windmills, solar cooking) than was previously the case may aid us in achieving a new sensitivity to our inter-relationship with the natural environment. As this attitude concerns owned land, we may come to regard ourselves as stewards rather than, or as well as, owners. Ecologically this land stewardship means that if the

The environment - land, sea, air and creatures - does change; and so the question arises, can the environment be changed intentionally to make it more fit, to make it more fitting for man and the other creatures of the world? Yes, but to do this one must know the environment, its creatures and their interactions - which is to say ecology. This is the essential pre-condition for planning - the formulation of choices related to goals and the means for their realization -
Ian McHarg
(DWN - 52)

We continually use solar energy whether we are conscious of it or not. For example, photosynthesis, sun tanning, insolation on buildings, light, weather, fossil fuels

If we are collecting solar heat we sure are going to be eager to see the sun, and we sure aren't going to want to waste it once we've caught it!

site does not benefit by the construction which we impose upon it, then we ought not to build.

We are learning how to more ecologically build on the land, both in a natural way and with technological innovations. Such information is not contained here (see the bibliography for hints on where to start). It is possible to find a lot of information on themes such as planting or harvesting, growing or killing, harnessing streams or letting them flow by, building on the top of a hill or on its side, recycling wastes or burying them. I wish that I could cover all these themes of ecological living, but I have attempted to deal most specifically with the use of solar energy in shelter design and less specifically with how the shelter (the built environment) fits more harmoniously and ecologically into the biosphere (the natural environment).

a design ethic

An ecological sensitivity can be regarded as a sort of reverance. It revolves around a very 'different' attitude about what is important, valuable, and beautiful in life. Monuments to man become less important; material possessions become valueless; and a built environment indiscriminately placed in the natural environment becomes ugly, no matter how 'elegant' the forms or how 'rich' the materials or how 'tasteful' and 'stylish' the 'lines'.

- Is a building necessary?
- Is there an abandoned building available?

Here are some general ecological principles when building:

- Use abundant local materials (to reduce transportation required, thereby decreasing energy consumption, and to improve local economy)
- Do not use products (except when they have a long, energy-conservative/producing life) which use in their construction, maintenance or function non-renewable natural resources such as redwood, gas, petroleum, copper, aluminum, lead, gold, mercury, silver, tin, zinc.
- Use long-lived, durable materials
- Return water and waste to the land
- Do the construction yourself
- Build simply
- Build permanently - make it last, make it durable
- Use lots of insulation
- Use waterproofing and other preservation methods

It's tempting to start by talking specifics, about not building in swamps or on flood plains, about things like the new 'miracle' insulations, or percolation beds, or even earth-covered roofs, but unless we reach some sort of agreement on the principles behind such architecture we may in the name of ecology do more harm than good -
Malcolm Wells
(AES - 433)

'Different': from today's usual standard

the farmer is the prototype. He prospers only insofar as he understands the land and his management maintains its bounty. So too with the man who

The Japanese have long been known for their spiritual sensitivity. Dr. Jiro Harada, in his book JAPANESE HOUSE AND GARDEN, recounts an example of such reverance in telling about Rikyu, a Japanese tea-master (OBH-5):

> When his new tea-room and garden were completed at Sakai he invited a few of his friends to a tea ceremony for the housewarming. Knowing the greatness of Rikyu, the guests naturally expected to find some ingenious design for his garden which would make the best use of the sea, the house being on the slope of a hill.
> But when they arrived they were amazed to find that a number of large evergreen trees had been planted on the side of the garden, evidently to obstruct the view of the sea. They were at a loss to understand the meaning of this. Later when the time came for the guests to enter the tea-room, they proceeded one by one over the stepping-stones in the garden to the stone water-basin to rinse their mouths and wash their hands, a gesture of symbolic cleansings, physically and mentally, before entering the tea-room. Then it was found that when a guest stooped to scoop out a dipperful of water from the water-basin, only in that humble posture was he suddenly able to get a glimpse of the shimmering sea in the distance by way of an opening through the trees, thus making him realize the relationship between the dipperful of water in his hand and the great ocean beyond, and also enabling him to recognize his own position in the universe; he was thus brought into a correct relationship with the infinite.

Sensitivity and reverance need not be quite so spiritual or esoteric. Lloyd Kahn, an author of DOMEBOOK I and DOMEBOOK II, summarized some things he's learned about shelter through his work with domes, (the form of which he has now renounced) (SBN):

> 1. Use of human hands is essential, at least in single-house structures. Human energy is produced in a clean manner, compared with oil-burning machines....
> 2. ...economy/beauty/durability: time. You've got to take _time_ to make a good shelter. Manual human energy....
> 3. The best materials are those that come from close by, with the least processing possible. Wood is good in damp climates, which is where trees grow. In the desert where it is hot and you need good insulation there is no wood, but plenty of dirt, adobe. Thatch can be obtained in many places, and the only processing required is cutting it.
> 4. Plastics and computers are way overrated in their possible applications to housing.

builds. IF he is perceptive to the processes of nature, to materials and to forms, his creations will be appropriate to the place; they will satisfy the needs of social process and shelter, be expressive and endure -

Ian McHarg
(DWN - 29)

someone called and wanted to know for
    whom I was living
and I said myself
and they said no I mean for Whom
and I said Myself

then someone called and wanted to know
    what I will be doing next year
and I said I didn't even know what I
    would be doing next second
and they said no I mean what do you
    want to Be.
and I said I Am.

someone called and wanted to know if
    people who never had their name
    in a newspaper are really alive
and I said yes
and they said but how can that be
and I said great

and then someone called and wanted to
    know where I will go when I leave
    the earth
and I said I cannot leave
and they said figuratively speaking.

and I said figuratively speaking I Am
    the earth.

\- Susan Thayer
(PYP - 113)

HE LOOKED UPON US AS SOPHISTICATED CHILDREN - SMART BUT NOT WISE -

Saxton T. Pope
(Said of Ishi)

5. there is a fantastic amount of information on building that has almost been lost.... many of the 100-year-old ways of building are more sensible right now.

Malcolm Wells, an ecologist/conservationist and a registered architect, expands upon these concepts and has developed specific criteria for evaluating the ecological success of a building (AES-434):

A. Build Reverently: Use the most abundant of local materials or those whose production seems to cause the least amount of damage to the land.
B. Build simply: Use as few materials as possible. But don't skimp on important things like first-class waterproofing and super-extra-double insulation. They'll repay your efforts for the life of the building, which brings up the need to
C. Build Permanently: Instant domes and throw-away buildings sound appealing but their use gives nature no time to heal the wounds of construction before the next round starts. Each time we move, uproot, repave, regrade, or break ground we tear the fragile fabric of life on the land, a fabric which may have taken decades or even centuries to develop. We must build hundred-year and two-hundred year buildings. Inside, their occupancy and decor can be changed whenever necessary, but for God's sake, no more ticky-tacky! It's too expensive.
D. Build Naturally: Make sure your project and its site, whether one house is involved or a thousand, do most of the following:
(1) create pure air (trees, shrubs, vines, grasses, wildflowers)
(2) create pure water (slow runoff, mulch, percolation)
(3) store rain water (ponding, percolation)
(4) produce their own food (this is a tough one!)
(5) create rich soil (mulch, compost)
(6) use solar energy (if you solve this one you'll get three Nobel prizes, and mankind will move ahead three giant steps)
(7) store solar energy (another Nobel for this one, too)
(8) create silence (dense plantings, sound insulations)
(9) consume their own wastes (live organically)
(10) maintain themselves (permanent materials, earth cover, good waterproofing)
(11) match nature's pace (build permanently)
(12) provide wildlife habitat (dense planting, berries, shelters)
(13) provide human habitat (a foregone conclusion)
(14) moderate climate and weather (windbreaks, dense groves of native plants)
(15) are beautiful (if you achieve the first 14, this one will be automatic)
E. Build Personally: We lost a precious thing when we became the only animals incapable of building their own nests. The miracle

It occurred to me lately that there is a profound difference between the way wood and rock are produced, and the way plastic foam and flexible vinyl windows are manufactured. Consider that a tree is rendered into "building material" by the sun, with a beautiful arrangement of minerals, water, and air into a good smelling, strong, durable building material. Moreover, trees look good as they grow, they help purify air, provide shade, nuts to squirrels, and colors and textures on the landscape. On the other hand, most plastics are derived by pumping oil from the earth, burning/refining/mixing it, with noxious fumes and poison in the rivers and ocean, etc. Of course, saw mills and lumber companies rip stuff up with gasoline motors and saws, smoke fumes, but it strikes me that the entire process of wood growing and cutting is preferable to the plastic production process. What is called for is tree-respecting forest management. This is something I intend to investigate as soon as I have time. -

Lloyd Kahn
(SBN)

Tony's zen-like shed, care and craftsmanship, the first thing he'd built, telling how it's being small keeps him outside a lot and that way he notices the seasons change....

Lloyd Kahn
(SBN)

that is a brick will be forever lost to the man who never lays one. Build with your hands as much as you can: you'll never regret it.

Altho all of these issues are important, this thesis deals primarily with how to use the sun in your built environment. You won't find Nobel-prize-winning solutions for solar energy collection or storage but you will be able to cut down on your shelter's loss of heat during the winter and collect and use solar energy. Such efforts will not only reduce your fuel bill but they will also reduce air-pollution and save our fast-depleting non-rénewable fossil fuels.

Lying under an acacia tree with the sounds of dawn around I became more aware of the basic miracle of life. Not life as applied humanly to man alone but life diversified by God on earth with superhuman wisdom forms as evolved by several million centuries of selection and environment. I realized that if I had to choose, I would rather have birds than airplanes -
(Charles Lindbergh)

THE HOUSE-HEATING PROBLEM

We recognize the global environmental problem and understand that the energy crisis (the shortage, its large consumption, its misuse, its waste, its polluting effects and our inability to harness certain types of energy) is a large part of this problem. "About 22% of the nation's energy consumption is for space heating" (NET-321). We will look at ways to affect this large use, both by decreasing the heat loss of buildings (houses in particular, here after referred to as shelters) and by finding ways to utilize the sun's energy, replacing the use of our rapidly depleting fossil fuels, as a means of heating and cooling these buildings (shelters in particular).

Let us first understand the economics of space heating. Seasonal heating cost is the sum of fuel cost, capital cost, and maintenance:

The analysis starts on the basis of the traditional economic guide for the measurement of practicality and feasible. Other considerations, such as government incentives or citizen responsibility (toward helping to solve the energy crisis) can also be considered.

$$\text{SEASONAL HEATING COST, \$/yr} = \text{FUEL COST} + \text{CAPITAL COST} + \text{MAINTENANCE}$$

$$\text{FUEL COST} = \frac{.0024\ F}{E}\left[D(A\overline{U} - cn) - g\right]$$

g = Heat gain from sources other than the traditional heating system: from appliances and other household functions; from insolation on the shelter or through windows; from solar energy collection and ventilation, from fireplaces. Btu/yr.

n = number of air changes in the shelter per hour, depending on family living pattern, weatherstripping, storm windows, etc.

c = Btu/°F: Heat capacity of the air in the shelter (=0.018 x house volume in cubic feet).

$A\overline{U}$ = Btu/°F/hr: $\Sigma A_j \overline{U}_j$; A_j represents the various kinds of area (windows, types of walls) composing the exterior skin of the building; $\overline{U}_j$ represents the various heat transfer coefficients through the various areas, BTU/Ft^2-°F - hr;

D = Degree days/yr: the sum (65 - t_a), for all days, a, of the heating season, where t_a is the average outdoor temperature for each day, a. (It is assumed that no heat is needed for outdoor temperatures 65°). See appendix II for some regional values of D.

F = Fuel cost, \$/10^5 Btu; (10^5 Btu = one therm). Net heating value: oil at 18.5¢/gal, natural gas at \$1.30/1000 cu. ft., and electricity at 0.48¢/KWh all correspond to 14¢/10^5 Btu. These prices rise faster than the price of living index.

E = Thermal efficiency of fuel used, percent:

Anthracite, hand-fired	60 - 75%
Bituminous coal, hand-fired	40 - 65%
Bituminous coal, stoker fired	50 - 75%
Oil and gas fired	65 - 80%
Electricity	100%

Poor furnace adjustment can reduce the above figures by 5 to 10. Electricity is really only about 30% efficient because of generation and transmission inefficiencies.

$$\text{CAPITAL COST} = \frac{C\,i}{100}$$

C = Capital expenditure, in dollars, on the complete heating system, house insulation, storm windows and doors, weatherstripping, and other items for heat-saving (glazing, shading, tree planting, materials used for thermal characteristics, length:width ratio of shelters, orientation of shelters to the sun; some of them begin to be without numerical value, being completely subjective in nature - we must somehow include such values, however we wish to assign them).

i = %/yr: interest plus depreciation on the capital investment.

$$\text{MAINTENANCE} = M$$

M = $/yr: the annual cost of maintenance of the heating system plus any difference in insurance rates between two possible systems.

The total seasonal heating cost then becomes

$$\text{SEASONAL HEATING COST} = \frac{.0024\ F}{E}\left[D(A\overline{U} + cn) - g\right] + C\,i + M$$

$$[\text{FUEL COST}] + [\text{CAPITAL COST}] + [\text{MAINTENANCE}]$$

(MOSTLY FROM NET-325)

A simple application of this equation to minimize seasonal heating cost is not possible because of the inaccuracies inherent in the various figures. For example, fuel efficiencies, E, vary depending on the particular furnace, its operating conditions, the thermostat on-off setting, and air-fuel ratios (efficiencies are usually lower than expected). The product $A\overline{U}$, the heat loss through the exterior skin, varies with quality of construction and with inaccuracies in experimental valves. The price of fuels, F, is constantly going up, and its value in 50 years, even in 5 years, is unpredictable. Determination of the air infiltration through cracks and openings in the exterior skin (for example around window sash and door jambs) and through open doors is educated guesswork.

The capital cost, C, of all items involved in the heat-saving/heat-providing effort is made complicated by the overlapping, dual roles of many of the items (such as windbreaks -- walls, fences, or trees -- which provide other additional amenities). The interest and depreciation, i, not only varies with the different items under capital cost but is also a function of prevailing interest rates, tax benefits, and accounting practices, not only complicating the process but also usually tending to make it appear that the lives of the building and of its heat-saving/heat-providing items are shorter than they really are (for example, what is the 'lifetime' of insulation? If its cost is amortized over a 20-year period, is it then 'worthless'?)

Maintenance, M, is difficult to figure at best. Manufacturers all claim maintenance-free products. The maintenance of a product can vary from installation to installation. Insurance costs vary from year to year, and are usually high for innovative methods such as solar energy.

But in spite of the complexity of the issues, we can make some simplifications as a basis for making comparisons and decisions between alternative energy-economic tradeoffs.

This thesis will first of all try to demonstrate methods of (1) lowering the heat loss of the shelter (decreasing in the seasonal heating cost the term $A\bar{U}$ + CN), (2) of increasing heat gain from other sources, g, especially through insolation on and into the shelter, and (3) of balancing that against increased capital costs, C.

The thesis will then try to show the effect of collecting, storing, and utilizing solar energy on cost, total energy consumption, and pollution. This will be done through a discussion of previous efforts in the field and through an analysis of what information is needed to make intelligent decisions in this field (I will provide a lot of this information). It will be seen that a percentage of the capital cost of the collection and storage system plus the seasonal

It is important that we first reduce the energy needed to heat the shelter and only then that we resort to alternative energy-producing methods (such as solar energy).

cost of operating this system must be less than the cost of the fuel which is saved through use of solar energy. By making adjustments in our economic and attitudinal values, we may find that the use of solar energy is more practical than previously supposed, when using traditional economic cost-benefit methods.

DESIGNING WITH THE SUN 2

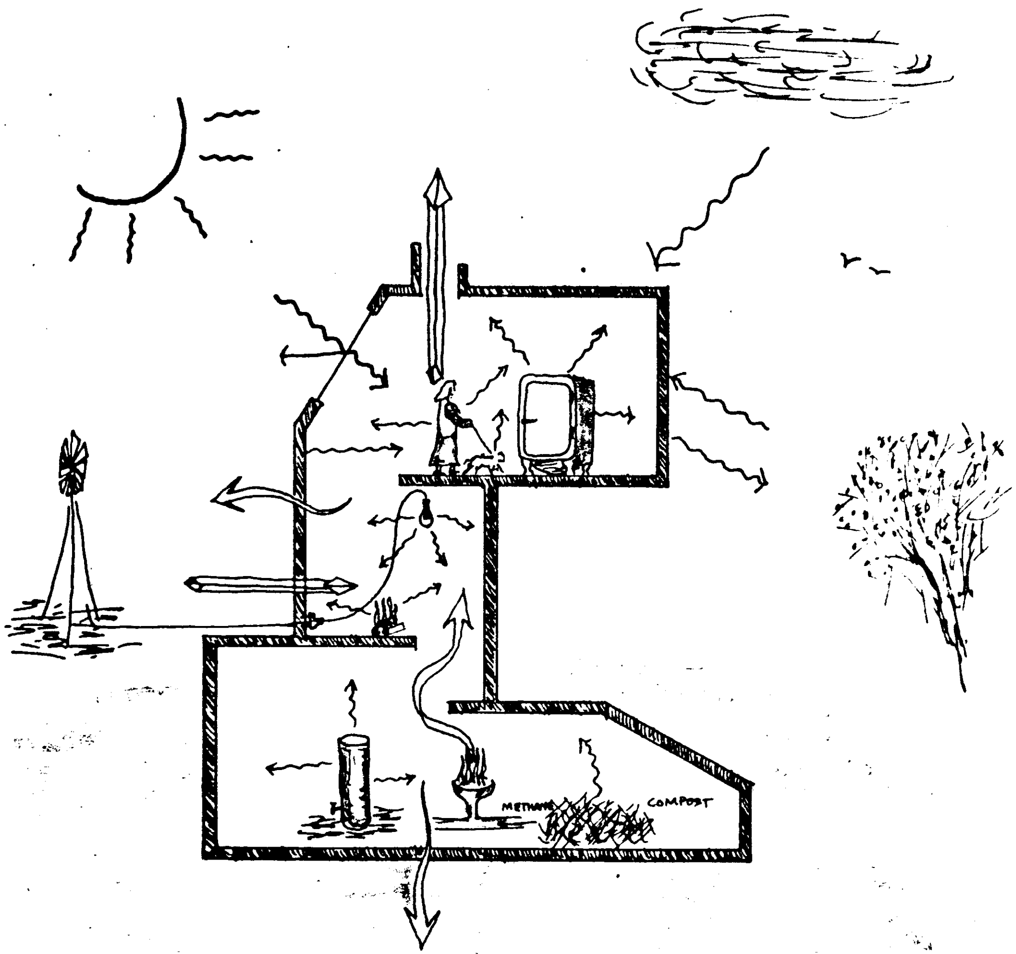
THE MAIN THRUST OF THE THESIS IS HEATING, AND DISCUSSION OF ENERGIES INVOLVED IN COOLING WILL ONLY BE OCCASIONAL.

THE PHYSIOLOGICAL FACTORS WHICH AFFECT HUMAN COMFORT ARE (ACA-44):

- PRODUCTION AND REGULATION OF HEAT IN THE HUMAN BODY.
- HEAT AND MOISTURE LOSSES FROM THE HUMAN BODY.
- THE EFFECTS OF COLD AND HOT SURFACES IN THE SPACE.
- THE STRATIFICATION OF AIR.
- EFFECTIVE TEMPERATURE: THE COMBINATION OF THE EFFECTS OF AIR TEMPEMPERATURE, MOISTURE CONTENT, AIR MOVEMENT.

AS DESIGNERS TRY TO ACHIEVE HUMAN COMFORT, EARTHS RESOURCES MUST BE USED AS WISELY AS POSSIBLE. THIS SECTION TRIES TO DECREASE OUR DEPENDENCE ON MAN-MADE TECHNOLOGIES WHICH REQUIRE CONTINUAL EXPENDITURE OF RESOURCES IN THEIR OPERATION. THIS IS DONE PRIMARILY THROUGH AN EFFORT TO LOSE LESS HEAT THROUGH THE SKIN OF THE HOUSE AND GAIN MORE HEAT FROM THE SUN.

THE DISCUSSION OF DECREASING HEAT LOSS INCLUDES THE EFFECTS OF INSULATION, WIND CONTROL, AND AIR INFILTRATION. CHARTS FOR MAKING QUICK ENERGY AND MONETARY ESTIMATES AS AN EVALUATION OF DIFFERENT DESIGN DECISIONS ARE PRESENTED. THE DISCUSSION OF EFFORTS TO INCREASE SOLAR HEAT GAIN INCLUDES THE EFFECTS OF BUILDING ORIENTATION, LENGTH-WIDTH RATIOS, HEAT-STORAGE CAPACITY OF MATERIALS, AND GLAZING.



IT IS CLEAR THAT A LOWER HEATING DEMAND CAN LOWER THE CONSUMPTION OF FOSSIL FUELS, THEREBY LOWERING FUEL COSTS AND REDUCING POLLUTION. IT IS HOPED THAT OWNER/USER PARTICIPATION WOULD INCREASE. SIMPLE PARTICIPATORY EFFORTS MIGHT INCLUDE: TURNING DOWN THE THERMOSTAT WHENEVER POSSIBLE (A 3°F REDUCTION FOR 8 HOURS PER DAY REDUCES FUEL BILLS BY 1% IN SOUTHERN CANADA. (SHEC-1)); DRAWING CURTAINS, PULLING SHADES, CLOSING VENETIAN BLINDS, CLOSING SHUTTERS; PUTTING ON STORM WINDOWS; WEATHERSTRIPPING WINDOWS AND DOORS; KEEPING THE FURNACE RUNNING CLEANLY, EFFICIENTLY; PUTTING UP TEMPORARY WINDBREAKS DURING WINTER....

heat transfer

HEAT MOVEMENT THROUGH WALLS (AND FLOORS AND CEILINGS) VARIES WITH
TYPE OF INSULATION
THICKNESS OF INSULATION
TYPE AND QUALITY OF CONSTRUCTION
WALL AREA
DIFFERENCE BETWEEN INSIDE AND OUTSIDE TEMPERATURE

THE OVERALL COEFFICIENT OF HEAT TRANSFER IS

$$U = \frac{1}{1/f_i + (x_1/k_1 + x_2/k_2 + \cdots) + 1/f_o} \qquad (1)$$

U = COEFFICIENT OF HEAT TRANSMISSION, Btu PER DEGREE FAHRENHEIT PER SQUARE FOOT PER HOUR (Btu/°F/ft²/hr).
x = THICKNESS OF A MATERIAL IN THE WALL, INCHES.
k = THERMAL CONDUCTIVITY OF A MATERIAL IN THE WALL, Btu PER DEGREE FAHRENHEIT PER SQUARE FOOT PER HOUR PER INCH THICKNESS (Btu/°F/ft²/hr/in).
f_i = CONDUCTANCE OF INSIDE AIR FILM, Btu PER DEGREE FAHRENHEIT PER SQUARE FOOT PER HOUR (Btu/°F/ft²/hr); TAKEN AS 1.5 FOR STILL AIR ∴ $1/f_i = 0.68$.
f_o = CONDUCTANCE OF OUTSIDE AIR FILM; TAKEN AS 6.0 Btu/°F/ft²/hr FOR A SURFACE EXPOSED TO THE WEATHER ∴ $1/f_o = 0.17$.
NOTE: f_i AND f_o ARE EXAMPLES OF 'CONDUCTANCES', C, HEAT FLOW THROUGH A GIVEN THICKNESS OF MATERIAL.

THE OVERALL HEAT TRANSFER PER HOUR IS

$$H_h = U\,(t_i - t_o) \qquad (2)$$

H_h = OVERALL HEAT TRANSFER, Btu PER SQUARE FOOT PER HOUR (Btu/ft²/hr).
t_i = INSIDE TEMPERATURE, DEGREE FAHRENHEIT (°F); USUALLY TAKEN AS 65°F.
t_o = OUTSIDE TEMPERATURE.

THE OVERALL HEAT TRANSFER PER SEASON IS

$$H_s = 24 \cdot U \cdot D \qquad (3)$$

H_s = OVERALL HEAT TRANSFER, Btu PER SEASON PER SQUARE FOOT (Btu/SEASON/ft²).
24 = HOURS PER DAY.
D = DEGREE DAYS PER SEASON (DAYS/SEASON); SEE APPENDIX II FOR SOME TYPICAL VALUES FOR THE UNITED STATES.

THE TOTAL HEAT TRANSFER THROUGH A SURFACE IS

$$Q = H_s A \qquad (4)$$

Q = TOTAL HEAT TRANSFER PER SEASON, Btu PER SEASON.
A = TOTAL SURFACE AREA WITH A GIVEN U, SQUARE FEET.

THE TOTAL COST OF HEAT TRANSFER IS

$$M = TQ \qquad (5)$$

M = TOTAL COST OF HEAT TRANSFER, DOLLARS PER SEASON ($/SEASON).
T = COST PER THERM (10^5 Btu) OF ENERGY DELIVERED TO THE HEATED SPACE, DOLLARS PER THERM ($/$10^5$ Btu); SEE CHART 'COST PER THERM OF ENERGY'.

→ USE MASSIVE AMOUNTS OF INSULATION
→ USE TRIPLE GLASS - NEVER ONLY SINGLE
→ COVER WINDOWS AT NITE - BEST WITH INSULATED SHUTTERS
→ 'BURY' THE WALLS IN EARTH

Learn the Language of Insulation

CONDUCTION—Heat will flow *through* any material, at a rate determined by the material's physical characteristics. Copper is an excellent conductor of heat; insulating materials are poor conductors.

CONVECTION—When two surfaces—one hot, the other cold—are separated by a thick layer of air, moving air currents (called convection currents) are established that carry heat from the hot to the cold surface. The process works like a thermal bucket brigade.

RADIATION—Any object that is warmer than its surroundings radiates heat waves (similar to light waves, but invisible) and, thus, emits heat energy.

BRITISH THERMAL UNIT (Btu)—A familiar measure of heat energy that is defined as the quantity of heat required to raise the temperature of one pound of water 1°F. Btu *per hour* are designated *Btuh.*

k, or THERMAL CONDUCTIVITY—A measure of the ability of a material to *permit* the flow of heat. It expresses the quantity of heat per hour that will pass through a one-square-foot chunk of inch-thick material when a 1°F temperature difference is maintained between its two surfaces; k is measured in Btuh.

C is similar, but measures the heat flow through a given thickness of material. If you know a material's k, to find its C just divide by the thickness. E.g: 3"-thick insulation with a k of 0.30 has a C of 0.10. The lower the k or C, the higher the insulating value.

U, or OVERALL COEFFICIENT OF HEAT TRANSMISSION—A measure of the ability of a complete building section (such as a wall) to *permit* the flow of heat. U is the combined thermal value of all the materials in a building section, plus air spaces and air films. The lower the U, the higher the insulating value.

R, or THERMAL RESISTANCE—A measure of ability to *resist* the flow of heat. R is simply the mathematical reciprocal of either C or U. Thus,

$$R = 1/C \text{ or } R = 1/U$$

depending on whether you're talking about the thermal resistance of a piece of insulation or a complete building section.

Insulation products are typically characterized by their R values. Thus, a specification of R-11 means the insulation displays 11 resistance units. Clearly, the higher the R value, the better the insulating ability.

R is a simple common denominator for describing *all* types of insulation and *all* kinds of dwelling construction. All insulation, for example, that is rated R-11 has the same insulation ability no matter what its material or thickness, as demonstrated in a chart, next page

THE ABOVE PROCESS IS GRAPHICALLY CONDENSED ON THE FOLLOWING PAGE, 'HEAT TRANSMISSION COST CHART', AS AN EFFORT TO AID THE DESIGN PROCESS.

USE THE OBLIQUE LINES REPRESENTING A PARTICULAR U-VALUE (COEFFICIENT OF HEAT TRANSMISSION, EQUATION (1)) TO START ON THE CHART AT POINT (1) OF THE EXAMPLE.

H_s (OVERALL HEAT TRANSFER PER SEASON, EQUATION (3)), IS REPRESENTED AT POINT (3), 'ENERGY THROUGH SURFACE'.

SQUARE FOOTAGE OF SURFACE, A, IS REPRESENTED BY THE NEXT SET OF OBLIQUE LINES.

POINT (5), 'ENERGY THROUGH TOTAL SURFACE', IS Q (TOTAL HEAT TRANSFER, EQUATION (4)).

THE NEXT SET OF OBLIQUE LINES (UPPER RIGHT GRAPH) REPRESENT VALUES OF T, COST PER THERM (10^5 BTU) OF ENERGY. THE PAGE FOLLOWING NEXT IS A CHART 'COST PER THERM OF ENERGY' WHICH HELPS TO DETERMINE THE THERM VALUE BASED ON COST OF ELECTRICITY, OIL, AND GAS.

M (TOTAL COST OF HEAT TRANSFER, EQUATION (5)), IS REPRESENTED AT POINT (7), 'TOTAL COST OF ENERGY'.

THE LAST GRAPH, BOTTOM RIGHT, CONVERTS THE COST TO 'REAL COST OF ENERGY' THROUGH THE USE OF OBLIQUE LINES, 'MULTIPLICATION FACTOR.' THIS FACTOR CAN BE ONE OR A COMBINATION OF SEVERAL THINGS:

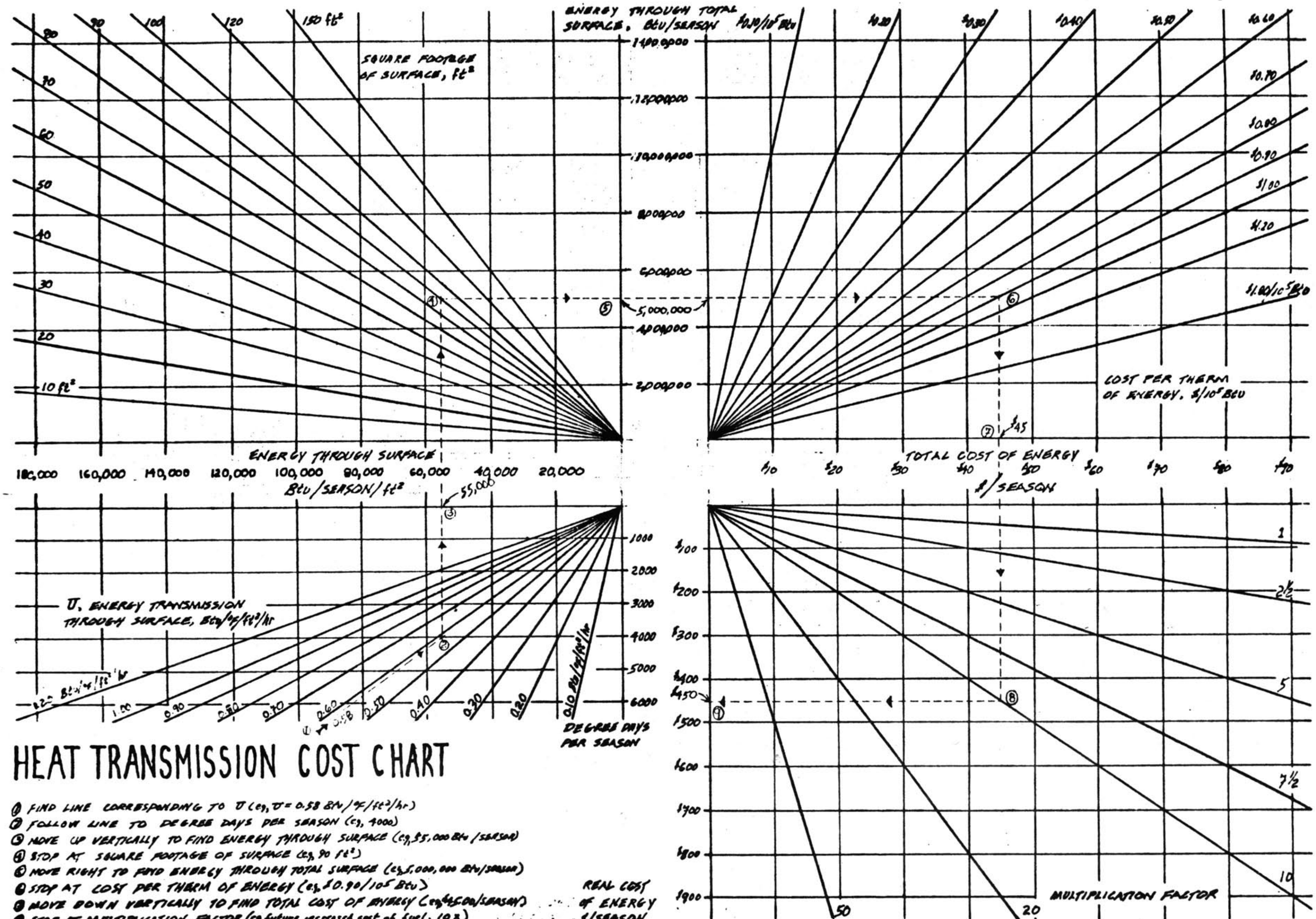
1) ESTIMATED FUTURE COST OF ENERGY: DESIGN DECISIONS BASED ON PRESENT ENERGY COSTS MAKE LITTLE SENSE AS COSTS SOAR.
2) REAL ENVIRONMENTAL COST OF USING FOSSIL FUELS: THIS PARTICULARLY INCLUDES POLLUTION AND THE DEPLETION OF NATURAL RESOURCES, BOTH DIRECTLY AS FUELS BURN AND INDIRECTLY AS THEY ARE BROUGHT TO THE CONSUMER FROM THE SOURCE.
3) INITIAL INVESTMENT COST: USE OF THE PROPER MULTIPLICATION FACTOR WOULD GIVE THE QUANTITY OF INCREASED INVESTMENT MADE POSSIBLE BY RESULTANT YEARLY FUEL SAVINGS.

NOTE:

IN STARTING THE CHART AT POINT (1), U CAN INSTEAD BE A ΔU, WHERE ΔU IS THE DIFFERENCE BETWEEN TWO KNOWN U-VALUES, FOR EXAMPLE, 0.55 FOR DOUBLE GLASS AND 0.36 FOR TRIPLE GLASS. ΔU IS THEN $0.55-0.36=0.19 \approx 0.2$. BY BEGINNING THE CHART WITH $U=0.2$, THE SAVINGS IN SEASONAL ENERGY COSTS CAN BE QUICKLY DETERMINED FOR THE USE OF TRIPLE GLASS INSTEAD OF DOUBLE. FOR A 5000 DEGREE DAY SEASON AND COST PER THERM OF ENERGY, $0.30, A 10 ft^2 WINDOW TRIPLE-GLAZED INSTEAD OF DOUBLE-GLAZED SAVES 230,000 BTU ($0.70) PER HEATING SEASON.

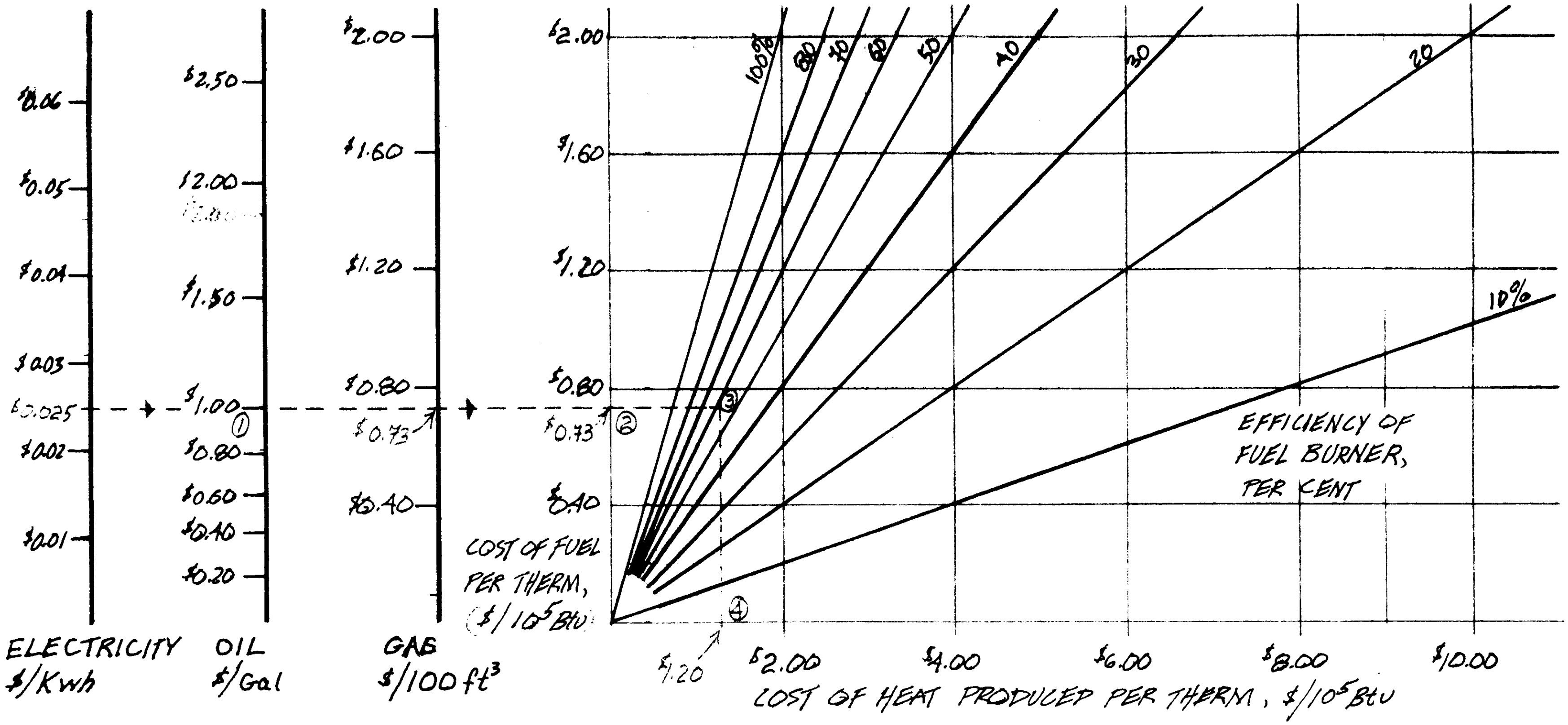
EACH OF THE CHARTS CAN BE USED INDEPENDENTLY OF ONE ANOTHER. FOR EXAMPLE, KNOWING A QUANTITY OF ENERGY AND ITS PRICE PER THERM, THE TOP RIGHT CHART GIVES THE TOTAL COST OF THAT ENERGY.

THE NUMERICAL VALUES OF EACH CHART CAN BE CHANGED BY A FACTOR OF TEN. FOR EXAMPLE, TO DETERMINE THE HEAT TRANSFER THROUGH A REAL GOOD EXTERIOR WALL, $U=0.05$, USE $U=0.5$ ON THE CHART AND DIVIDE THE FINAL ANSWER BY TEN.



HEAT TRANSMISSION COST CHART

1. FIND LINE CORRESPONDING TO U (e.g., U = 0.58 Btu/°F/ft²/hr)
2. FOLLOW LINE TO DEGREE DAYS PER SEASON (e.g., 4000)
3. MOVE UP VERTICALLY TO FIND ENERGY THROUGH SURFACE (e.g., 55,000 Btu/SEASON)
4. STOP AT SQUARE FOOTAGE OF SURFACE (e.g., 90 ft²)
5. MOVE RIGHT TO FIND ENERGY THROUGH TOTAL SURFACE (e.g., 5,000,000 Btu/SEASON)
6. STOP AT COST PER THERM OF ENERGY (e.g., $0.90/10⁵ Btu)
7. MOVE DOWN VERTICALLY TO FIND TOTAL COST OF ENERGY (e.g., $45.00/SEASON)
8. STOP AT MULTIPLICATION FACTOR (e.g., future increased cost of fuel, 10×)
9. MOVE LEFT TO FIND REAL COST OF ENERGY (e.g., $450.00/SEASON)



COST PER THERM OF ENERGY

① FIND POINT ON VERTICAL COLUMN CORRESPONDING TO KNOWN RETAIL PRICE OF FUEL (eg, $1.00/gal for OIL ≙ $0.025/kwh for ELECTRICITY ≙ $0.73/100ft³ for GAS)

② MOVE RIGHT TO FIND RETAIL COST OF FUEL PER THERM (eg $0.73/10⁵ Btu)

③ STOP AT EFFICIENCY OF FUEL BURNER (eg, 60%)

④ MOVE DOWN TO FIND REAL COST OF HEAT PRODUCED PER THERM (eg, $1.20/10⁵ Btu)

NOTE: THERE ARE 3412 Btu/kwh ELECTRICITY; 135,000 Btu/gal OIL; 1000 Btu/ft³ GAS.
PRICE PER THERM IS OFTEN AVAILABLE FROM UTILITY COMPANIES.
"COST OF HEAT PRODUCED PER THERM" CAN BE USED WITH OTHER CHARTS IN THESIS.

HEATING EFFICIENCIES OF SOME FUEL BURNERS, PER CENT

ANTHRACITE COAL, HAND-FIRED	60-75
BITUMINOUS COAL, HAND-FIRED	40-65
BITUMINOUS COAL, STOKER-FIRED	50-70
OIL & GAS FIRED	65-80
DIRECT ELECTRIC HEATING	100

NOTE: POOR FURNACE ADJUSTMENT CAN REDUCE THE ABOVE FIGURES BY 5-10.
ELECTRICITY GENERATION & TRANSMISSION LOSES 2 Btu PER Btu DELIVERED.

U values

THE OVERALL COEFFICIENT OF HEAT TRANSFER, U, HAS BEEN DEFINED AS

$$U = \frac{1}{1/f_i + (x_1/k_1 + x_2/k_2 + \cdots) + 1/f_o} \qquad (1)$$

UNDER NORMAL CONDITIONS, THE VALUES IN THE DENOMINATOR ($1/f_i$, x_1/k_1, ...) ARE 'RESISTANCES' TO HEAT FLOW – THE LARGER THE RESISTANCE, THE SMALLER IS THE U-VALUE, AND THE SMALLER IS THE HEAT FLOW. U BECOMES THEN

$$U = \frac{1}{R_1 + R_2 + R_3 + \cdots}$$

WHERE R_1 MIGHT REPRESENT $1/f_i$ (= 0.68 °F-ft²-hr/Btu),
R_2 MIGHT REPRESENT $1/f_o$ (= 0.17 °F-ft²-hr/Btu), AND
R_3 AND R_4 AND R_5 .... MIGHT REPRESENT ALL OF THE VALUES OF X/K. (IT HAS BEEN SHOWN THAT $1/f_i$ AND $1/f_o$ ARE EXAMPLES OF 'CONDUCTANCE', THE OPPOSITE OF RESISTANCE: $R = 1/C$. FOR GIVEN THERMAL RESISTANCE OR INSULATIVE PROPERTIES OF MATERIALS, K, C, 1/K, 1/C, AND R ARE ALL USED TO SOME EXTENT. SEE APPENDIX III FOR SOME TYPICAL VALUES.)

U CAN THEN BE FOUND BY FIRST ADDING $R_1 + R_2 + R_3 + \ldots$ AND THEN DIVIDING IT INTO ONE (TAKING THE RECIPROCAL). THE ANSWER IS IN Btu/°F/ft²/hr, AS SHOWN BELOW:

MATERIAL	K or C	R (1/C or X/K)
STILL AIR FILM INSIDE	1.46	0.68
STILL AIR FILM OUTSIDE	6.0	0.17
MATERIAL #1, e.g. EXTERIOR CLADDING, X_1 THICK	K_1	X_1/K_1
MATERIAL #2, e.g. INSULATION, X_2 THICK	K_2	X_2/K_2
MATERIAL #3, e.g. INTERIOR FINISH	C_1	$1/C_1$

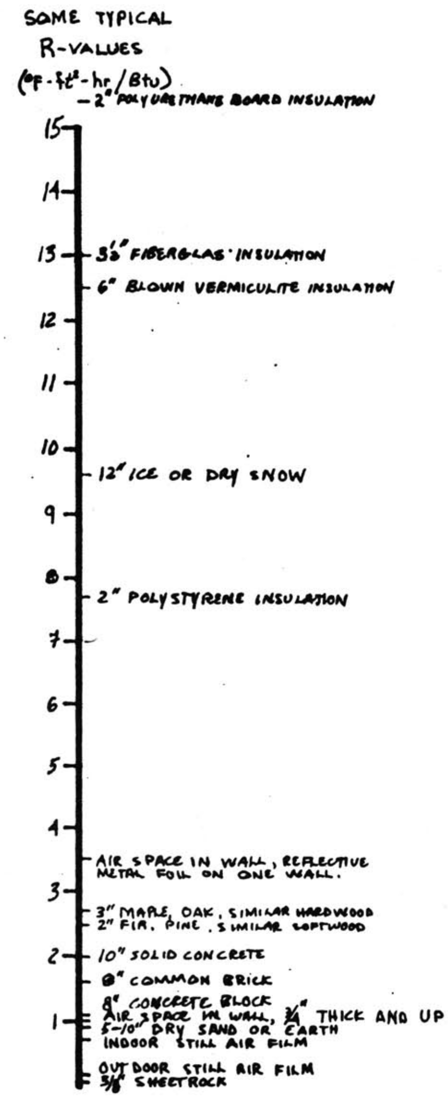
THE TOTAL RESISTANCE, $R_t = R_1 + R_2 + R_3 + R_4 + R_5$

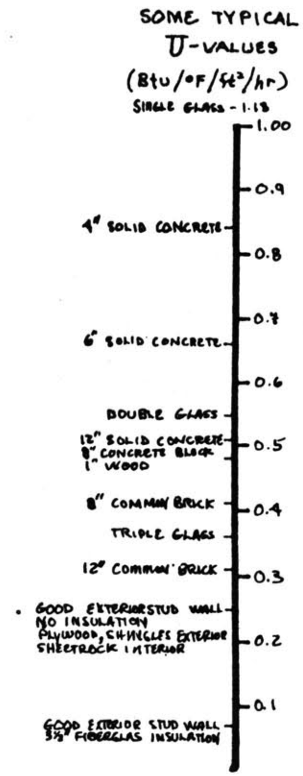
$$= 0.68 + 0.17 + X_1/K_1 + X_2/K_2 + 1/C_1$$

$$= 0.85 + X_1/K_1 + X_2/K_2 + 1/C_1$$

U THEN IS

$$U = 1/R = \frac{1}{0.85 + X_1/K_1 + X_2/K_2 + 1/C_1}$$





IT CAN BE SEEN THAT IT TAKES MUCH GREATER AMOUNTS OF THERMAL RESISTANCE, R, TO SIGNIFICANTLY LOWER A SMALL U-VALUE THAN TO LOWER A LARGER ONE. FOR EXAMPLE, ADDING 2" OF POLYURETHANE INSULATION (R≈15) TO 8" OF SOLID CONCRETE REDUCES U FROM 0.66 TO 0.059. ADDING THE SAME INSULATION TO A GOOD EXTERIOR STUD WALL REDUCES U FROM 0.07 TO 0.034. THIS IS SHOWN MATHEMATICALLY:

THE THERMAL RESISTANCE, R, FOR AN INITIAL U-VALUE, U_i, IS

$$R_i = \frac{1}{U_i}$$

IF WE ADD THERMAL RESISTANCE (FOR EXAMPLE, INSULATION), R_{IN}, TO R_i WE HAVE A NEW RESISTANCE, R_f:

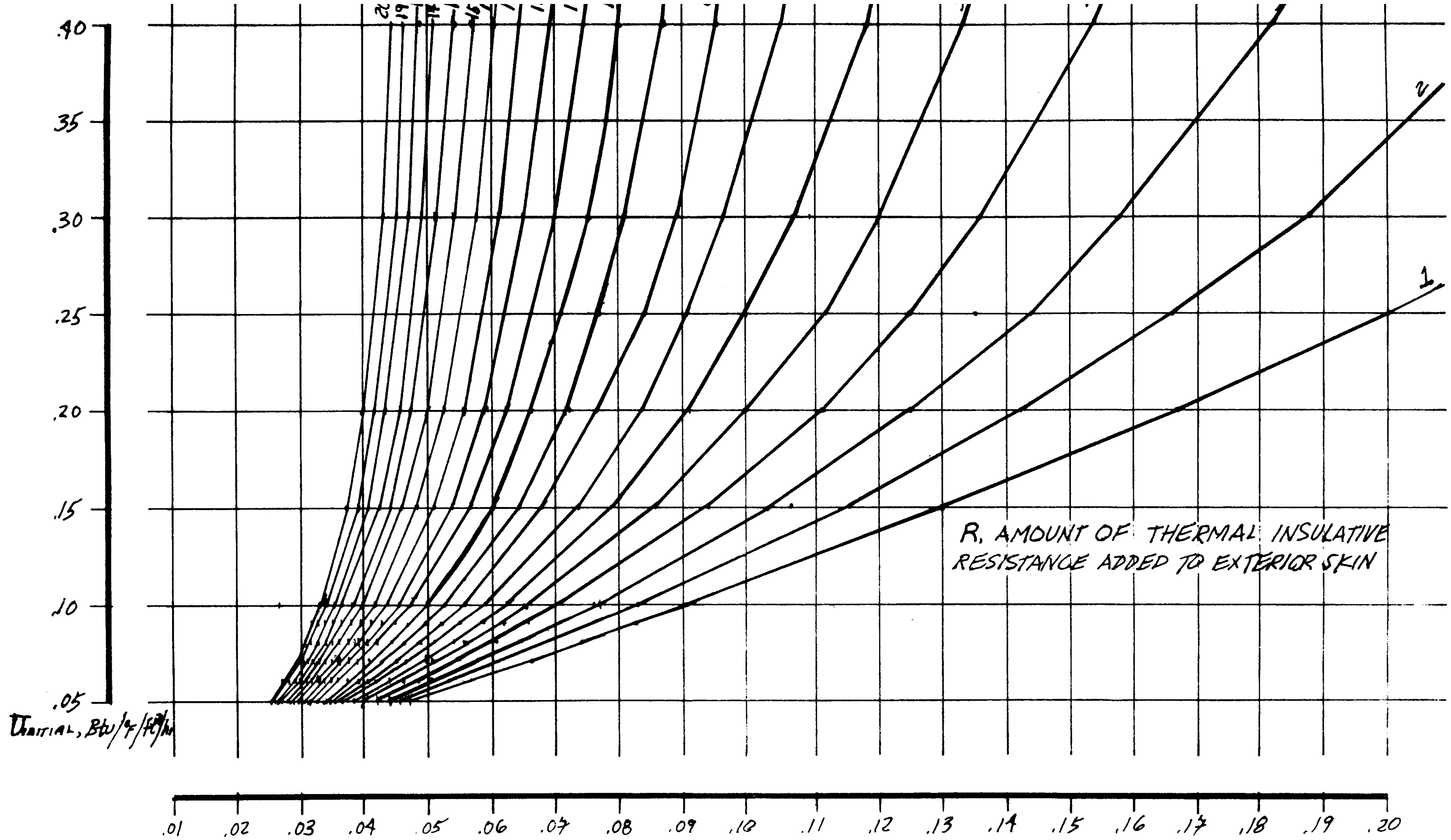
$$R_f = R_i + R_{IN} = \frac{1}{U_i} + R_{IN} = \frac{1}{U_f}$$

AND

$$U_f = \frac{1}{R_f} = \frac{1}{1/U_i + R_{IN}}$$

$$\therefore \quad U_f = \frac{U_i}{1 + U_i R_{IN}}$$

THE EFFECT OF ADDING THERMAL RESISTANCE, R_{IN}, TO A U-VALUE, U_i, IS SHOWN GRAPHICALLY IN THE FOLLOWING CHART, 'IMPACT OF CHANGE IN THERMAL RESISTANCE ON HEAT TRANSMISSION VALUE'. THE ECONOMIC IMPACT OF SUCH A CHANGE CAN BE READILY ASCERTAINED BY USING ΔU ($= U_i - U_f$) AS THE U-VALUE AT POINT ① ON THE 'HEAT TRANSMISSION COST CHART'. FOR THE EXAMPLE ABOVE OF ADDING 2" POLYURETHANE TO 8" CONCRETE, $\Delta U = 0.66 - 0.059 \approx 0.6$. FOR THE CHART, FOR U = 0.6 Btu/hr/ft²/F°, DEGREE DAYS = 5000/SEASON, AND COST PER THERM OF ENERGY = $0.30/10⁵ Btu, WE FIND THAT ONE SQUARE FOOT OF SUCH APPLICATION SAVES IN ONE HEATING SEASON ABOUT 71,000 Btu AND $0.21 IN FUEL BILLS (THAT ABOUT HALF THE COST OF THE INSULATION). IF WE ARE WILLING TO INVEST TWENTY TIMES THAT AMOUNT NOW TO SAVE THAT AMOUNT IN YEARLY OPERATING BILLS, WE CAN INVEST $4.20/ft² TO ACHIEVE THE ΔU OF 0.6. OR, IF WE ESTIMATE THAT FUEL COSTS WILL RISE BY A FACTOR OF 2½ IN THE NEXT 10 YEARS, THE YEARLY SAVINGS IN FUEL AT THAT TIME WILL BE $0.53/ft².



U_{FINAL}, Btu/°F/ft²/hr : OBTAINED BY ADDING AN AMOUNT OF THERMAL INSULATIVE RESISTANCE, R, TO AN EXTERIOR SKIN WITH A COEFFICIENT OF HEAT TRANSMISSION, $U_{INITIAL}$.

NOTE: THE ECONOMIC RETURN OF $U_i - U_f$ CAN BE FOUND ON THE 'HEAT TRANSMISSION COST CHART', STARTING AT STEP ①.

IMPACT OF CHANGE IN THERMAL RESISTANCE ON HEAT TRANSMISSION VALUE

'basement' walls

HEAT LOSS THROUGH BASEMENT WALLS HAS BEEN MEASURED FOR SOLID CONCRETE AND CONCRETE BLOCK WALLS (SEE TABLE BELOW), BUT USING THESE STANDARD ENGINEERING VALUES RESULTS IN A GREATER HEAT LOSS THROUGH BASEMENT WALLS IN SIX MONTHS (ONE HEATING SEASON) THAN THROUGH GOOD STUD WALLS EXPOSED TO THE WEATHER. FOR EXAMPLE, USING A 4.0 Btu/ft²/hr HEAT LOSS THROUGH THE BASEMENT WALLS, AND A STUD WALL WITH A U-VALUE OF 0.07, AND 5000 DEGREE DAYS PER SEASON, WE FIND THAT THE BASEMENT WALL LOSES:

Ground Water Temperature	Basement Floor Loss,[a] Btu/Sq Ft/hr	Below Grade Wall Loss,[b] Btu/Sq Ft/hr
40	3.0	6.0
50	2.0	4.0
60	1.0	2.0

[a] Based on basement temperature of 70 F and U of 0.10.
[b] Assumed twice basement floor loss.

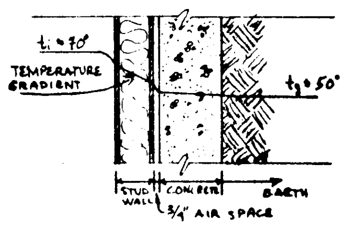
(HOF-460)

$$(4.0\ Btu/ft^2/hr)(182\ days/season)(24\ hr/day) = 18{,}000\ Btu/season/ft^2$$

THE STUD WALL LOSES:

$$(0.07\ Btu/°F/ft^2/hr)(5000\ DD/season)(24\ hr/day) = 9000\ Btu/season/ft^2$$

CAN IT BE TRUE THAT A BASEMENT WALL LOSES TWICE AS MUCH HEAT AS A STUD WALL (EXPOSED TO WEATHER) OVER THE COURSE OF A HEATING SEASON?! THE DATA SAYS YES. BUT SUPPOSE THAT THE BASEMENT WALL IS INSULATED TO THE EXTENT THAT THE STUD WALL IS? NO DATA IS GIVEN, AND IT IS DIFFICULT TO CONJECTURE BECAUSE THE OUTSIDE AIR FILM FOR NORMAL HEAT LOSS CALCULATIONS HAS BEEN REPLACED BY SOLID EARTH. BUT WE KNOW THAT THE OUTSIDE AIR FILM HAS A RESISTANCE, R = 0.17. IF WE WERE TO BUILD A TYPICAL EXTERIOR STUD WALL, U = 0.07, AS SHOWN BELOW, WITH A 3/4" AIR SPACE BETWEEN IT AND THE CONCRETE (IN AN EFFORT TO SIMULATE THE OUTSIDE AIR FILM - THE AIR SPACE HOWEVER DOES HAVE GREATER THERMAL RESISTANCE THAN THE AIR FILM), WE CAN ASSUME THAT AT THERMAL EQUILIBRIUM THE STUD WALL WILL BE 'SEEING' A TEMPERATURE AT THE FACE OF THE CONCRETE WALL ABOUT THE SAME AS THAT OF THE GROUND, t_g.



SECTION

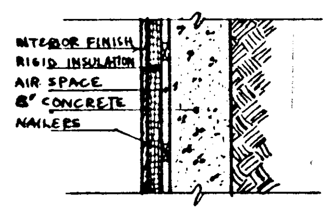
FOR A $t_g = 50°F$ AND $t_i = 70°F$, WE HAVE A $\Delta t = t_i - t_g = 20°F$. FOR THERMAL DESIGN PURPOSES, $t_i = 65°F$ INSTEAD OF 70°F, AND WE HAVE A Δt OF 15°. HEAT LOSS THROUGH THE STUD WALL BECOMES

$$U\Delta t = 0.07(15°) \doteq 1\ Btu/ft^2/hr$$

THIS IS ABOUT ONE-FOURTH OF THAT FOR THE CONCRETE WALL ALONE AND ABOUT HALF OF THAT FOR THE EXTERIOR STUD WALL. THUS, BY BERMING EARTH UP AROUND WALLS WHICH HAVE A U-VALUE APPROXIMATING THAT OF A GOOD STUD WALL, CONSIDERABLE ENERGY SAVINGS CAN BE REALIZED.

OF COURSE, IN PRACTICE WE WOULD NOT BUILD SUCH A STUD WALL IN THE BASEMENT. BUT WE MIGHT APPLY INSULATION TO THE CONCRETE. IF WE DID, WE MIGHT FIRST FASTEN 'NAILERS' OR 'SLEEPERS' TO THE CONCRETE (TO GET THE 'FREE' INSULATIVE AIR SPACE) AND THE APPLY RIGID INSULATION ON TOP OF THAT, AS SEEN TO THE LEFT, FASTENING THE INTERIOR FINISH ON TOP OF THE INSULATION, POSSIBLY WITH NAILS THROUGH TO THE NAILERS. IF 1" POLYURETHANE WERE USED AS INSULATION, THE U-VALUE, FROM INTERIOR TO CONCRETE FACE, WOULD BE ABOUT 0.11 Btu/°F/ft²/hr. DURING A HEATING SEASON, THIS WALL WOULD LOSE ABOUT 7000 Btu/ft², FOR A FUEL SAVINGS OVER THE UNINSULATED CONCRETE OF ABOUT $0.02/ft²/SEASON.

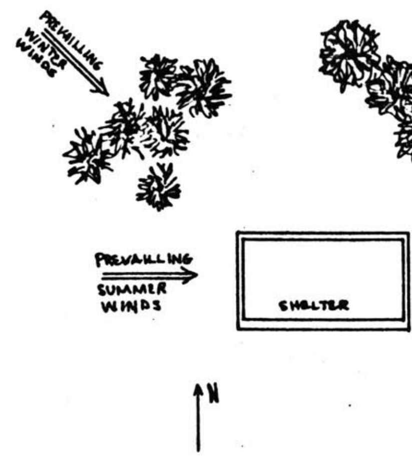
OF COURSE, BY SOMEHOW PUTTING THE INSULATION BETWEEN THE CONCRETE AND THE GROUND, WE INCREASE THE EFFECTIVE HEAT STORAGE MASS OF THE SHELTER BY INCLUDING THE CONCRETE IN THAT MASS. SEE 'HEAT STORAGE CAPACITY OF MATERIALS.'

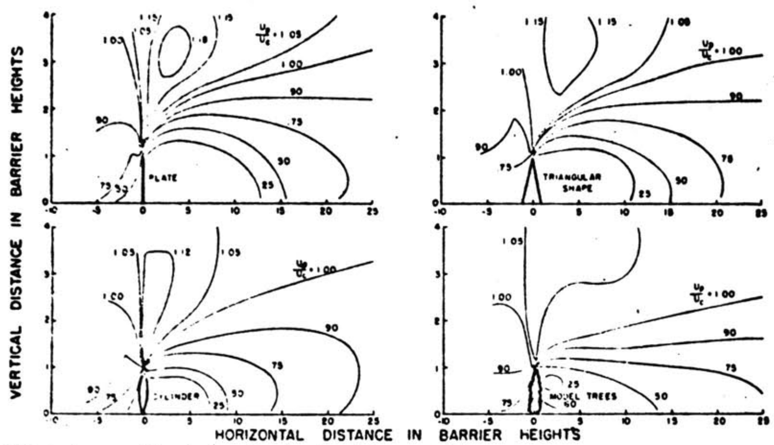


SECTION

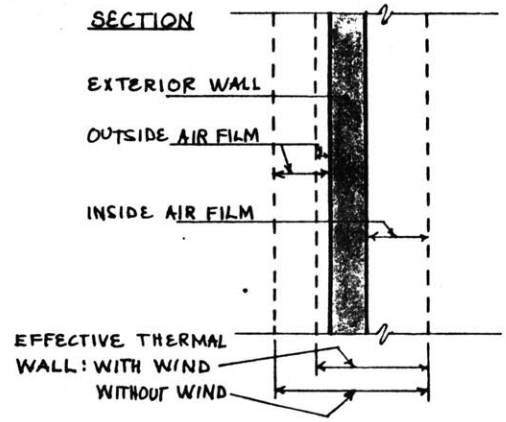
wind control and heat transfer loss

OLGYAY REPORTS (DWC-99) THAT A 20 mph WIND DOUBLES THE HEAT LOAD OF A HOUSE THAT IS NORMALLY EXPOSED TO 5 mph WINDS, AND "A SHELTER-BELT'S [OF TREES] EFFECTIVENESS INCREASES AT HIGHER WIND VELOCITIES." FUEL SAVINGS COULD BE AS HIGH AS 30% WITH GOOD PROTECTION ON THREE SIDES OF A HOUSE.



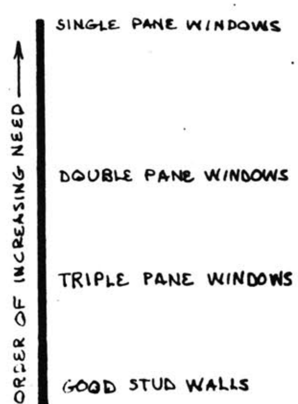


190. Air flow around four barriers of varying shape. (DWC-9B)



EXAMPLE: A SINGLE PANE OF GLASS HAS
- U = 1.13 Btu/°F/ft²/hr FOR 15 mph WIND
- IF WIND IS REDUCED BY 10-20 mph FOR ENTIRE SEASON, WE MAY HAVE
- ΔU ≈ 0.20
- FOR A 5000 DD HEATING SEASON,
- ENERGY SAVED IS ≈ 25,000 Btu/season/ft²
- FOR $0.30 PER THERM OF ENERGY, TEN- 10 ft² WINDOWS, AND A MULTIPLICATION FACTOR OF 20,
- REAL SAVINGS IS $130.00/SEASON/100 ft²

EXAMPLE: DOUBLE GLASS (3/4" AIR SPACE)
- U = 0.55 Btu/°F/ft²/hr FOR 15 mph WIND
- WIND REDUCTION OF 10-20 mph FOR ENTIRE SEASON GIVES
- ΔU ≈ [illegible]
- FOR SAME CRITERIA AS ABOVE
- ENERGY SAVED IS ≈ 12,000 Btu/SEASON/ft²
- REAL ENERGY SAVINGS IS ≈ $65.00 SEASON/100 ft²



RELATIVE IMPORTANCE OF SURFACES RECEIVING WIND PROTECTION

EXAMPLE: TRIPLE GLASS (3/4" AIR SPACES)
- U = 0.36 Btu/°F/ft²/hr FOR 15 mph WIND
- A 10-20 mph WIND REDUCTION FOR THE SEASON RESULTS IN
- ΔU ≈ 0.06
- FOR A 5000 DD HEATING SEASON, A $0.30 COST PER THERM, AND TEN 10 ft² WINDOWS
- ENERGY SAVED IS ≈ 7,200 Btu/SEASON/ft²
- FOR A MULTIPLICATION FACTOR, 20
- REAL COST OF ENERGY SAVED IS ≈ $37.00/SEASON/100 ft²

EXAMPLE: TYPICAL STUD WALL
- U ≈ 0.10 Btu/°F/ft²/hr
- A 10-20 mph WIND REDUCTION MIGHT REDUCE THIS BY
- ΔU ≈ 0.05
- FOR THE SAME CRITERIA AS ABOVE
- ENERGY SAVED IS ≈ 600 Btu/SEASON/ft²
- REAL ENERGY SAVINGS FOR 500 ft² IS ≈ $16.00/SEASON/500 ft²

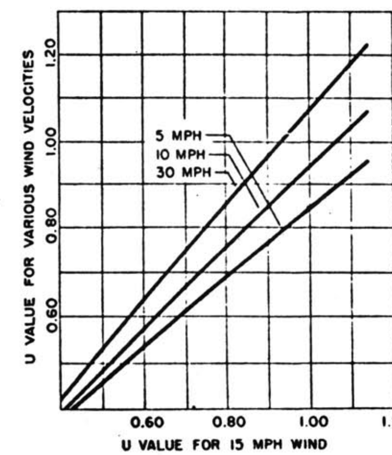


Fig. 1.23—Variation in U value versus wind velocity. (WAG-28)

TABLE 4.5. Air Infiltration Through Windows* (ACA-76)

Expressed in cubic feet per ft of crack per hour†

Type of Window	Remarks	Wind Velocity, MPH 5	10	15	20	25	30
Double-hung wood sash windows (unlocked)	Around frame in masonry wall—not calked‡	3	8	14	20	27	35
	Around frame in masonry wall—calked‡	1	2	3	4	5	6
	Around frame in wood frame construction‡	2	6	11	17	23	30
	Total for average window, non-weather-stripped, 1/16-in. crack and 3/64-in. clearance.§ Includes wood frame leakage‖	7	21	39	59	80	104
	Ditto, weatherstripped‖	4	13	24	36	49	63
	Total for poorly fitted window, non-weather-stripped, 3/32-in. crack and 3/32-in. clearance.¶ Includes wood frame leakage‖	27	69	111	154	199	249
	Ditto, weatherstripped‖	6	19	34	51	71	92
Double-hung metal windows**	Non-weather stripped, locked	20	45	70	96	125	154
	Non-weather stripped, unlocked	20	47	74	104	137	170
	Weather stripped, unlocked	6	19	32	46	60	76
Rolled section steel sash windows¶¶	Industrial pivoted, 1/16-in. crack††	52	108	176	244	304	372
	Architectural projected, 1/32-in. crack‡‡	15	36	62	86	112	139
	Architectural projected, 3/64-in. crack‡‡	20	52	88	116	152	182
	Residential casement, 1/64-in. crack§§	6	18	33	47	60	74
	Residential casement, 1/32-in. crack§§	14	32	52	76	100	128
	Heavy casement section, projected, 1/64-in. crack‖‖	3	10	18	26	36	48
	Heavy casement section, projected 1/32-in. crack‖‖	8	24	38	54	72	92
Hollow metal, vertically pivoted window**		30	88	145	186	221	242

* From "Heating Ventilating Air-Conditioning Guide 1957." Used by permission.

† The values given in this table, with the exception of those for double-hung and hollow metal windows, are 20 per cent less than test values to allow for building up of pressure in rooms and are based on test data reported in the papers listed in chapter references.

‡ The values given for frame leakage are per foot of sash perimeter as determined for double-hung wood windows. Some of the frame leakage in masonry walls originates in the brick wall itself and cannot be prevented by calking. For the additional reason that calking is not done perfectly and deteriorates with time, it is considered advisable to choose the masonry frame leakage values for calked frames as the average determined by the calked and non-calked tests.

§ The fit of the average double-hung wood window was determined as 1/16-in. crack and 3/64-in. clearance by measurements on approximately 600 windows under heating season conditions.

‖ The values given are the totals for the window opening per foot of sash perimeter and include frame leakage and so-called *elsewhere* leakage. The frame leakage values included are for wood frame construction but apply as well to masonry construction assuming a 50 per cent efficiency of frame calking.

¶ A 3/32-in. crack and clearance represent a poorly fitted window, much poorer than average.

** Windows tested in place in building.

†† Industrial pivoted window generally used in industrial buildings. Ventilators horizontally pivoted at center or slightly above, lower part swinging out.

‡‡ Architecturally projected made of same sections as industrial pivoted except that outside framing member is heavier, and it has refinements in weathering and hardware. Used in semi-monumental buildings such as schools. Ventilators swing in or out and are balanced on side arms. 1/32-in. crack is obtainable in the best practice of manufacture and installation, 3/64-in. crack considered to represent average practice.

§§ Of same design and section shapes as so-called *heavy section casement* but of lighter weight. 1/64-in. crack is obtainable in the best practice of manufacture and installation, 1/32-in. crack considered to represent average practice.

‖‖ Made of heavy sections. Ventilators swing in or out and stay set at any degree of opening. 1/64-in. crack is obtainable in the best practice of manufacture and installation, 1/32-in. crack considered to represent average practice.

¶¶ With reasonable care in installation, leakage at contacts where windows are attached to steel framework and at mullions is negligible. With 3/64-in. crack, representing poor installation, leakage at contact with steel framework is about one-third and at mullions about one-sixth of that given for industrial pivoted windows in the table.

→ WEATHERSTRIP COMPLETELY!

→ USE FEWER OPERABLE WINDOWS; USE INSTEAD 'OPERABLE WALLS' TO VENTILATE.

→ COVER WINDOWS WITH INSULATED SHUTTERS (OR CURTAINS, SHADES, ETC) AT NITE.

HEAT LOSS DUE TO AIR INFILTRATION, H_i, THROUGH WINDOW AND DOOR CRACKS IS GIVEN AS

$$H_i = g \cdot c \cdot d \cdot L (t_i - t_o) \text{ Btu/hr}$$

g = AIR INFILTRATION PER HOUR, AS GIVEN IN THE TABLE TO THE LEFT; CUBIC FEET OF AIR PER HOUR PER FOOT LENGTH OF CRACK ($ft^3/hr/ft$).

c = SPECIFIC HEAT OF AIR, ≈ 0.24 Btu/lb/°F.

d = DENSITY OF AIR, ≈ 0.075 lb/ft^3.

L = LENGTH OF CRACK, APPROXIMATELY THE SUM OF ALL LENGTHS OF WINDOW-TO-FRAME CONNECTIONS (USUALLY THE PERIMETER OF THE WINDOW OR DOOR); GIVEN IN FEET.

$t_i - t_o$ = INDOOR-OUTDOOR TEMPERATURE DIFFERENCE, DEGREE FAHRENHEIT (°F). FOR A TOTAL HEATING SEASON, THIS BECOMES THE PRODUCT OF (DEGREE DAYS/SEASON) x (24 hrs/DAY).

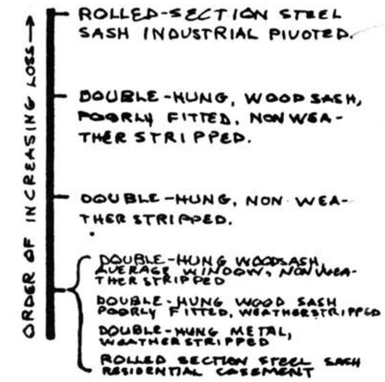
FOR AIR INFILTRATION HEAT LOSS PER SEASON WE HAVE

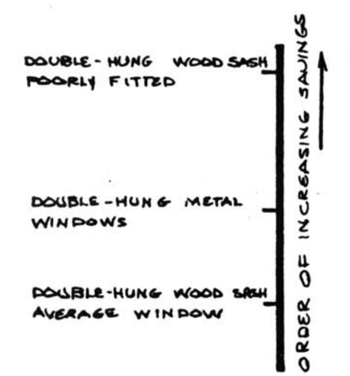
$$H_i = K g L (DD) \text{ Btu/SEASON}$$

K = A CONSTANT: 24 c d = (24 hrs/DAY) x (0.24 Btu/lb/°F) x (0.075 lb/ft^3) = 0.432 Btu-hrs/°F/ft^3/DAY.

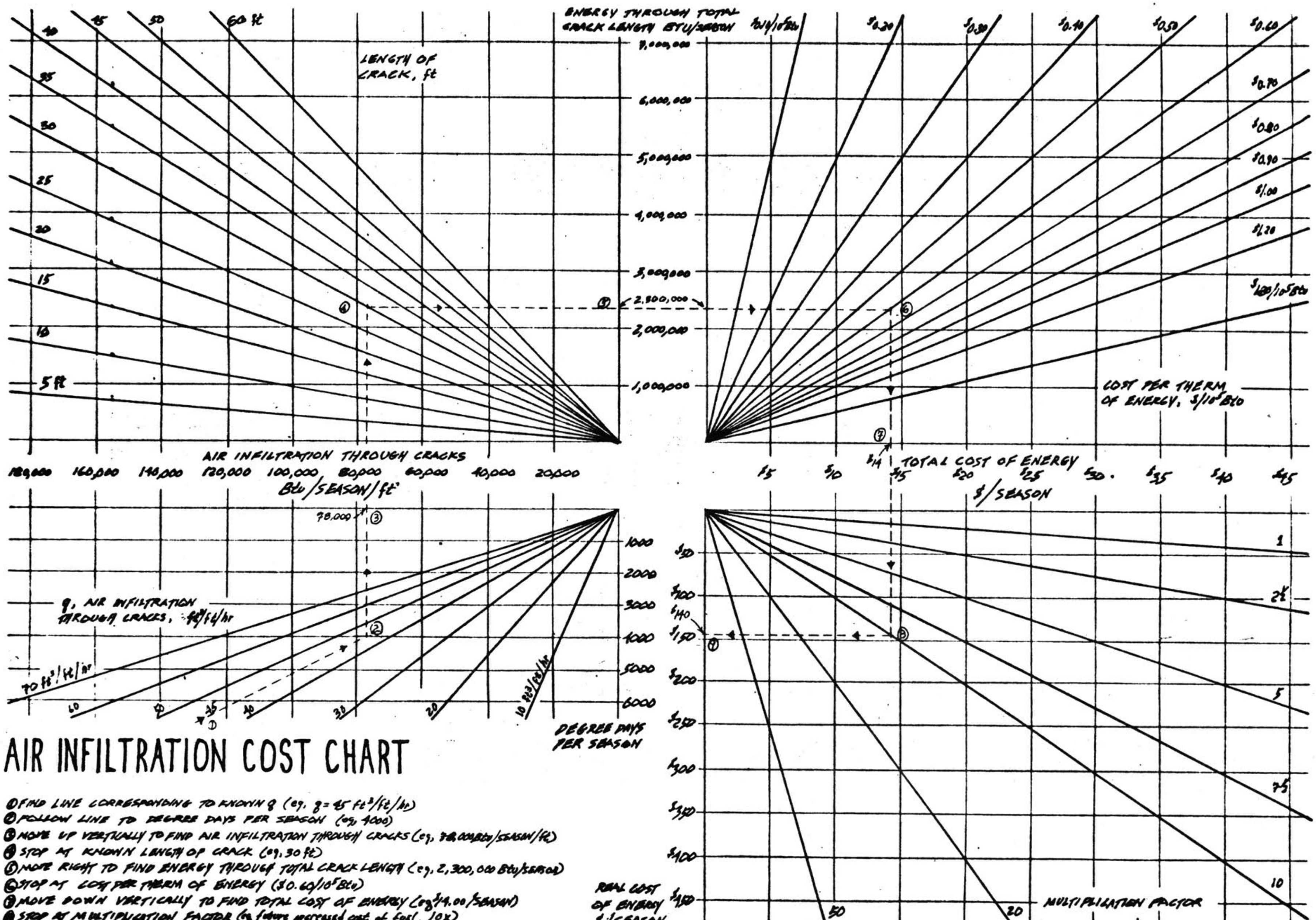
BY USING THE 'AIR INFILTRATION COST CHART' (ON THE NEXT PAGE) AND THE TABLE TO THE LEFT, WE CAN QUICKLY FIND THE DIFFERENCE IN ENERGY LOSS BETWEEN WEATHERSTRIPPED AND NON-WEATHERSTRIPPED WINDOWS. FOR THE EXAMPLES, WIND VELOCITY IS 15 mph; THERE ARE 5000 DEGREE DAYS PER SEASON AND 15 FEET OF CRACK LENGTH; A THERM (10^5 Btu) OF ENERGY COSTS $.30/$10^5$ Btu; A MULTIPLICATION FACTOR OF 2.0 IS USED. THE EXAMPLES ARE ON THE PAGE FOLLOWING NEXT.

RELATIVE AIR INFILTRATION LOSSES PER SEASON USING VARIOUS WINDOWS





RELATIVE SAVINGS IN AIR INFILTRATION LOSSES BY WEATHERSTRIPPING VARIOUS WINDOW TYPES



AIR INFILTRATION COST CHART

1. FIND LINE CORRESPONDING TO KNOWN q (eg. q = 45 ft³/ft/hr)
2. FOLLOW LINE TO DEGREE DAYS PER SEASON (eg. 4000)
3. MOVE UP VERTICALLY TO FIND AIR INFILTRATION THROUGH CRACKS (eg. 78,000 Btu/SEASON/ft)
4. STOP AT KNOWN LENGTH OF CRACK (eg. 30 ft)
5. MOVE RIGHT TO FIND ENERGY THROUGH TOTAL CRACK LENGTH (eg. 2,300,000 Btu/SEASON)
6. STOP AT COST PER THERM OF ENERGY ($0.60/10^5 Btu)
7. MOVE DOWN VERTICALLY TO FIND TOTAL COST OF ENERGY (eg. $14.00/SEASON)
8. STOP AT MULTIPLICATION FACTOR (eg. future increased cost of fuel, 10X)
9. MOVE LEFT TO FIND REAL COST OF ENERGY (eg. $140.00/SEASON)

EXAMPLES FROM PAGE BEFORE LAST (RESULTS BASED ON THE CRITERIA THEREIN MENTIONED.)

EXAMPLE: <u>DOUBLE-HUNG WOOD SASH AVERAGE WINDOW</u>
- FROM THE TABLE, THE DIFFERENCE IN AIR INFILTRATION, q, FOR WEATHERSTRIPPED VERSUS NONWEATHERSTRIPPED IS 39-24 = 15 $ft^3/hr/ft$.
- FROM THE CHART, TOTAL ENERGY SAVED IS ≈ 48,000 Btu/SEASON.
- THE REAL SAVINGS IN ENERGY COSTS IS $30.00/SEASON.

EXAMPLE: <u>DOUBLE-HUNG METAL WINDOWS</u>
- FROM THE TABLE, THE DIFFERENCE IN AIR INFILTRATION FOR WEATHERSTRIPPED VERSUS NONWEATHERSTRIPPED IS 74-32 = 42 $ft^3/hr/ft$.
- FROM THE CHART, TOTAL ENERGY SAVED IS ≈ 1,400,000 Btu/SEASON.
- THE REAL SAVINGS IN ENERGY COSTS IS $80.00/SEASON.

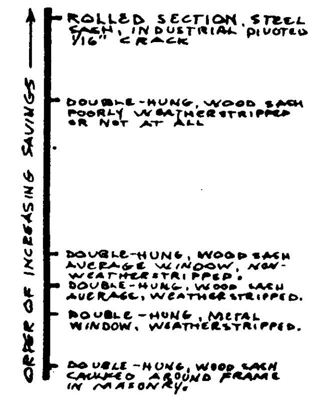
EXAMPLE: <u>DOUBLE-HUNG WOOD SASH AVERAGE WINDOW WEATHERSTIPPED VERSUS THE SAME WINDOW OF METAL</u>
- FROM THE TABLE, THE DIFFERENCE IN AIR INFILTRATION IS 32-24 = 8.
- FROM THE CHART, TOTAL ENERGY SAVED IS ≈ 260,000 Btu/SEASON.
- THE REAL SAVINGS IN ENERGY COSTS IS $15.00/SEASON.

WIND CONTROL

AS CAN BE SEEN FROM THE TABLE, THE WIND PLAYS A LARGE ROLE IN THE VOLUME OF AIR WHICH COMES IN THROUGH THE CRACKS. THE FOLLOWING EXAMPLES HELP TO SHOW THIS EFFECT. AS IN THE PREVIOUS EXAMPLES, THERE ARE 5000 DEGREE DAYS PER SEASON, 15 FEET OF CRACK LENGTH, A THERM VALUE OF $0.80/$10^5$ Btu, AND A MULTIPLICATION FACTOR OF 20.

EXAMPLE: <u>DOUBLE-HUNG WOOD SASH AVERAGE WINDOW, NONWEATHERSTRIPPED.</u>
- FOR A 20 mph WIND REDUCTION DURING THE HEATING SEASON, THE DIFFERENCE IN AIR INFILTRATION IS ABOUT 60 to 80 $ft^3/hr/ft$.
- FROM THE CHART, TOTAL ENERGY SAVED IS ≈ 2,000,000 Btu/SEASON.
- THE REAL SAVINGS IN ENERGY COSTS IS ≈ $125.00/SEASON.

RELATIVE SAVINGS IN AIR INFILTRATION LOSS THRU VARIOUS WINDOWS BY REDUCING WIND VELOCITY



EXAMPLE: <u>DOUBLE-HUNG WOOD SASH AVERAGE WINDOW, WEATHERSTRIPPED.</u>
- FOR A 20 mph WIND REDUCTION DURING THE SEASON, THE DIFFERENE IN AIR INFILTRATION IS ABOUT 50 $ft^3/hr/ft$.
- FROM THE CHART, TOTAL ENERGY SAVED IS ≈ 1,600,000 Btu/SEASON.
- REAL SAVINGS IN ENERGY COSTS IS ≈ $100.00/SEASON.

EXAMPLE: <u>DOUBLE-HUNG METAL WINDOW, WEATHERSTRIPPED</u>
- FOR A 20 mph WIND REDUCTION DURING THE HEATING SEASON, THE DIFFERENCE IN AIR INFILTRATION IS ABOUT 55 $ft^3/hr/ft$.
- FROM THE CHART, TOTAL ENERGY SAVED IS ≈ 1,800,000 Btu/SEASON.
- REAL SAVINGS IN ENERGY IS ≈ $110.00/SEASON.

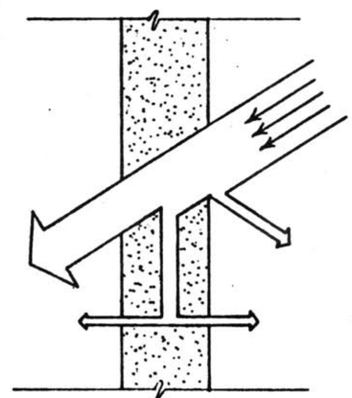
SOLAR HEAT GAIN

Since we are concerned with decreasing total heating demand, we should at the initial design stages, attempt to increase the heat gain from solar insolation (but attempt to decrease it during hot weather). Customarily, solar gains have not been entered into the computation of seasonal heating demand. When engineers size a furnace, they design for the coldest days when there is no sun. This is right and logical, but building designers should have tools to help them to reduce total seasonal energy consumption for heating. Unfortunately, most research done on solar gain is for hot weather conditions to aid in making design decisions for cooling and refrigeration. The data which is applicable to heating is difficult to understand and even harder to use in the design process. Translation of this data into useful design tools is is partly begun here but extensive work in this area would be of great benefit in helping to lower our energy needs.

glazing

Openings in shelters, once without the benefits of glass, were used for the passage of people and their accompanying possessions, for the passage of air providing natural ventilation, and for the passage of natural light to the interiors. These openings also allowed the people to look out, an opprtunity which most of us require when we spend time indoors.

But the openings also prevented the people from having control of some of the detrimental qualities of openness: animals and bugs had free access; the inside temperature was difficult to regulate; air movement, humidity, and air cleanliness could not be controlled.



SECTION THROUGH GLASS
188 Btu/ft²/hr ON A TYPICAL, CLEAR AFTERNOON IN MID-SUMMER AT 40°N LATITUDE FACING SOUTHWEST

Although pieces of glass have been dated as far back as 2300 BC, its use in windows probably did not occur until the time of Christ. Only in the last 75 years has it become economically and technologically possible to produce and use panes of glass larger than eight or twelve inches on a side.

As technology and economics improve, glass is increasingly being used to replace the traditional solid (masonry or wood) exterior wall. But the design problems accompanying this substitution have often been ignored.

Besides reducing the electrical energy required for lighting, glass exposed to sunlight admits heat in the manner shown in the diagram on the previous page. Experimental houses have been built with the major parts of south-facing walls being entirely of glass. G F Keck designed such a house near Chicago that was sponsored by Illinois Institute of Technology. Heat savings may have been as high as 18%, and the house became overheated on clear winter days.(SHH - 69) Other 'solar houses' have been reported to have saved up to 30% in fuel bills. The 'greenhouse effect' is primarily responsible for this phenomenon. Glass readily transmits the short-wave light radiation as shown in the graph on the right but does not readily transmit in the other direction the long-wave thermal radiation resulting when the light energy changes to heat energy as it hits an interior surface.

The ASHRAE Handbook of Fundamentals gives massive tables on solar heat gain for latitudes 24, 32, 40, 48, and 52° N for the twenty-first day of each month. But these erudite tables are next to impossible for a designer to use as a source of obtaining a quick estimate of solar heat gain. The designer should be able to find out by looking at a chart (or several charts), how many Btu's of solar energy will enter through a wall or window detail.

The HANDBOOK discusses means of predicting 'Solar and Total Heat Transfer Through Fenestration Areas'. (HOF -476,7) This article ex-

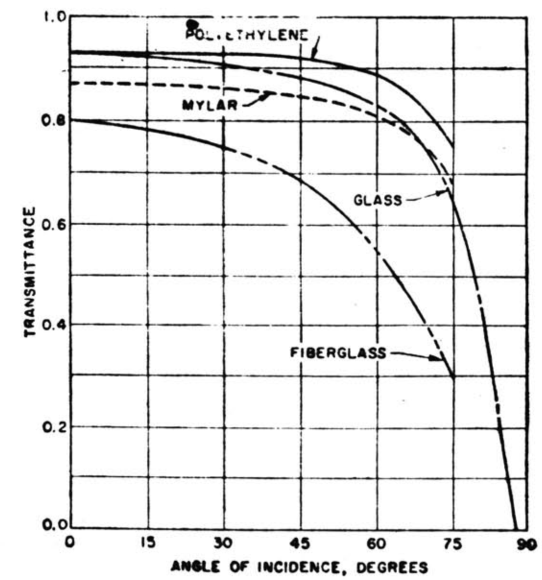


Fig. 12 .... Transmittance of Solar Radiation Through Glazing Materials for Various Angles of Incidence (ASHRAE GUIDE -191)

plains that heat transfer through glass is affected by several factors, among them:

1. Solar radiation intensity, $\dot{I}_t$, and incident angle, θ. (figure 1)
2. Outdoor-indoor temperature difference. When the sun is not shinging, heat flows according to the usual laws of heat transfer (primarily):

$$H = U(t_i - t_o)$$

This phenomenon was discussed in the section, "Heat Loss Through the Exterior Skin"

The glass becomes hot when the sun shines on it, and heat then flows by radiation and convection from its outer surface to the atmosphere and the surrounding environment, and from its inner surface to the room air. The rate of heat flow inward by radiation and convection from an unshaded single glass is:

total heat admission through glass = solar heat gain + conduction heat gain

$$H = (N_i) \times \left(\text{ABSORBED SOLAR RADIATION} = \alpha I_t\right) + U(t_o - t_i)$$

N_i is the inward-flowing fraction of absorbed radiation. For unshaded single glazing, $N_i = U/f_o$, and H becomes

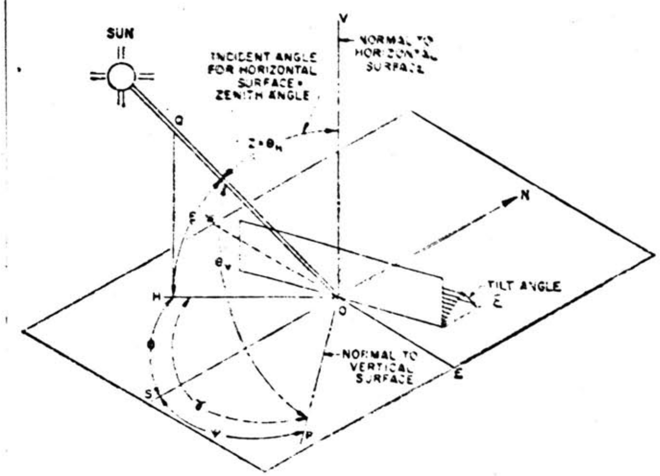
$$H = U\left(\frac{\alpha I_t}{f_o} + t_o - t_i\right)$$

α=absorptance of solar radiation by the glass, percent; the opposite of reflectivity. (See Appendix IV for values of some common materials)

I_t=incident solar radiation, Btu per suare foot per hour (Btu/ft^2/hr).

H, U, f_o, t_o AND t_i were all defined before.

3. Velocity and direction of air flow across the



SOLAR ALTITUDE, β = ∠ QOH
ZENITH ANGLE, Z = ∠ QOV
WALL AZIMUTH, ψ = ∠ SOP

SOLAR AZIMUTH, φ = ∠ SOH
INCIDENT ANGLE, θV = ∠ QOP
WALL - SOLAR AZIMUTH = ∠ HOP

To find the wall-solar azimuth for other orientations,

For walls facing East of South:
$\gamma = \phi - \psi$ a.m.
$\gamma = \phi + \psi$ p.m.

For walls facing West of South:
$\gamma = \phi + \psi$ a.m.
$\gamma = \phi - \psi$ p.m.

Treat negative values of γ as if they were positive. If γ is greater than 90 deg, the surface is in the shade.

Fig. 3 .... Solar Angles for Vertical and Horizontal Surfaces (HOF)

exterior fenestration surfaces. This phenomenon was also discussed earlier in this section under "Wind Control".
4. Low temperature radiation exchange between the surface of the fenestration and the surroundings. This phenomenon is difficult to predict - it is assumed to be included in the outer and inner surface coefficients (air films), f_o and f_i .

Since α, I_t, and f_o vary greatly, primarily because of the incident angle between the sun and the glass, the HANDBOOK has provided the tables previously mentioned. (HOF - 470-4)

Extensive work on the concept of 'solar house' was done by F W Hutchinson at Purdue University. In 1945, under a grant from Libbey-Owens-Ford Glass Company, two nearly identical houses were built side by side. The only difference was that one of the houses had considerably more south-facing glass (two ¼" clear glass panes separated by a ½" air space; $U = 0.53$ Btu/°F/ft^2/hr). (SHO - 55) During the first winter season, the solar house used 16.3% more heating energy than did the house of orthodox construction. Inspite of this, Hutchinson reported in May 1947 that "the available solar gain for double windows in south walls in most cities in the USA is more than sufficient to offset the excess transmission loss through the glass." (SHAR - 90)

The main design problem of south-facing windows becomes that of making sure that the thermal heat capacity of the inside of the building is great enough to absorb and store the excess heat so that the interior space does not require venting. The better the insulative value of the walls and windows, the less heat will be lost through heat transmission and the greater will the heat capacity need to be. This is shown in the graph where the inside temperature in the unheated solar house was 80° on January 15 while outside it was below freezing.

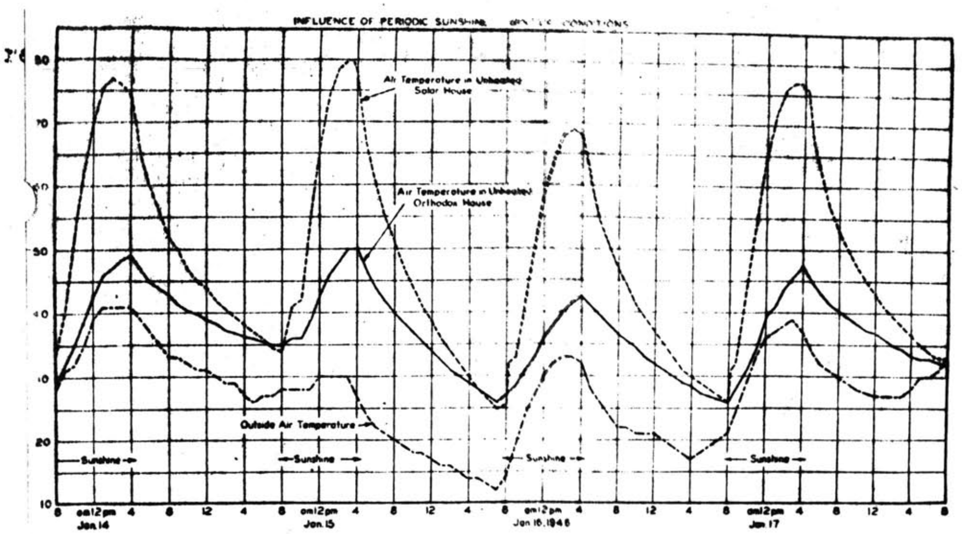


Fig. 3. **Test results from operation of both houses without any heating.** (SHAR - 92)

It must be pointed out that large glass areas require a larger first cost of a heating system because of the extra heat loss involved through the glass which would otherwise be solid wall. Also, for a given latitude, solar intensity does not vary (although cloudiness does), but heat loss does vary according to the outside temperature. It follows then that the use of glass in mild climates has greater potential for reducing seasonal heating demand than it does in cold climates at the same latitude.

The quantity of solar energy which gets through a south-facing window on an average sunny day in the winter is more than that which is received through that same window on an average sunny day in summer. There are a number of reasons for this:

1. Although there are more daylight hours during the summer than during the winter, there are more hours of possible sunshine on a south-facing window in winter than in summer. For example, at latitude 35° N, there are 14 hours of possible sunshine on June 21, but the sun remains north of east until after 8:30 am and goes to north of west before 3:30 pm, so that direct sunshine occurs for only 7 hours on the south-facing wall. But on

December 21, the sun is on the south wall for the full 10 hours that it is above the horizon.
2. The intensity of insolation on a plane normal to the sun's rays is approximately the same in summer as in winter. The extra distance that they must travel through the atmosphere is offset by the sun's being closer to the earth during the winter than during the summer.
3. Since the sun is closer to the horizon during the winter, the rays strike the windows at more nearly right angles than they do in the summer when the sun is at a higher altitude. At 35°N, 150 units of energy may strike a square foot of window during an average winter hour; during the summer this number would be 100 units.
4. Winter sky radiation (due to the scattering effect of the atmosphere) is twice the amount of summer sky radiation.
5. The more nearly the sun's rays hit the window at right angles, the greater the transmittance (shown earlier). They are more nearly so in winter than in summer.
6. With proper shading, the window can be shielded from most of the direct summer radiation.

Hutchinson's conclusions are that more than twice as much solar radiation is transmitted through south-facing windows in winter as in summer. If in summer the windows are shaded, the difference is even greater.

The following chart, prepared by Hutchinson, can be used as a design tool to approximate solar heat gain through windows for the seven-month heating season. The effects of window type and latitude are relatively small compared with normal outside temperature and per-cent of sunshine.

These two values can be found in the table on the page following the next for about 48 cities in the US. The first column gives the ratio, F, of the average number of sunshine hours during the heating

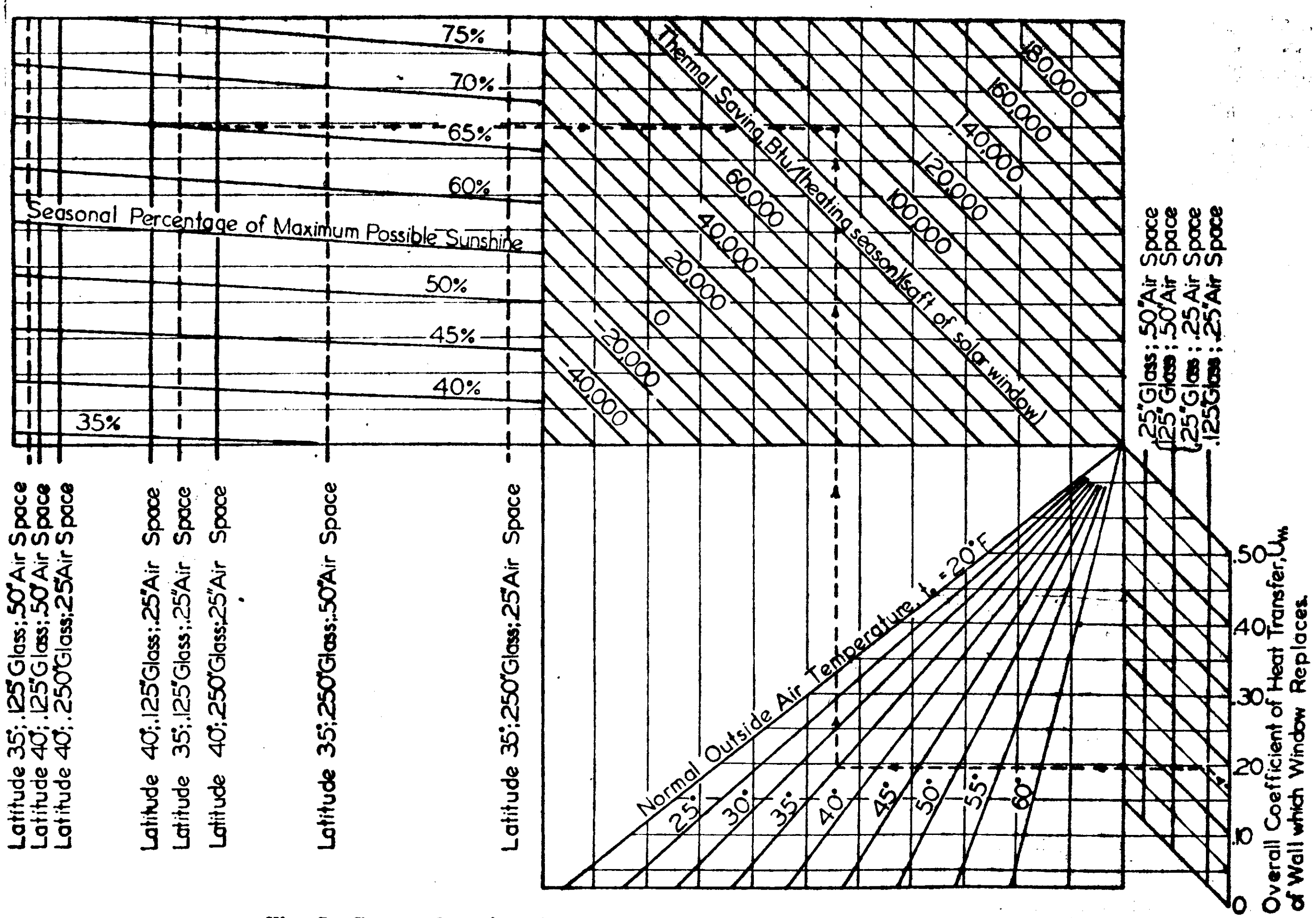


Fig. 5—Seasonal saving (or loss) attributable to 1 sq ft of double glass window replacing an equal area of south wall with solar overhang of roof (RBS-116

(Note that the opaque wall area is not credited with any effective seasonal solar energy utilization)

Example: A window consisting of two identical sheets of 1/8 in. clear plate glass separated by a 1/4 in. air space is to be used in a south wall which has an overall coefficient of heat transfer of 0.165 Btu/(hr) (sq ft) (F). The normal outside temperature for the locality is 35 F and the sun shines for 65 per cent of the maximum possible hours between October 1 and May 1. Latitude is 40 degrees.

Solution: Enter bottom of the upper left quadrant of Fig. 5 at the heavy vertical line which is identified as applicable to 1/8 in. glass with 1/4 in. air space at 40 deg latitude. Rise along this line to intersection with line for 65 per cent sunshine then move horizontally right (see dashed example line) to enter upper right quadrant. Now re-enter the figure at value of $U_w = 0.165$ on scale at right of lower right quadrant. Follow the directrix line from point of entry to intersection with vertical for 1/8 in. glass, 1/4 in. air space, 40 deg latitude; then move horizontally left to intersect curve for $t_o = 35$ deg and from this point move vertically upward to intersect the horizontal line already established in the upper right quadrant. The point of intersection of these two lines gives the answer as 107,000 Btu saved per seven month heating season per square foot of window.

season (October 1 to May 1) to maximum possible sunshine hours. The last two columns show transmission losses through single and double windows; such losses are for use in sizing the heating plant for a shelter but have little significance with respect to operating cost.

The fourth and fifth columns give net gain of energy (a negative number represents a loss) resulting in the use of one square foot of single or double glass. All 48 cities show net energy gains through the double glass. The losses shown through the single glass in some cities would have to be compared (using Hutchinson's chart and the 'Heat Transmission Cost Chart' in this thesis) with the heat loss thru the wall it was replacing. The approximate seasonal heat gain is the product of the value in column four or five times the window area times the number of hours in the heating season. Of course, there will be many days when all of this heat cannot be used. Often, too, other factors such as human desires to pull a shade or close the curtains will reduce solar gain. The analysis does not take into account solar gain of south walls. Hutchinson's work showed that this factor can be significant.

(SHAR)

City	Fraction, F, of maximum possible sunshine.	Normal temperature during seven month heating season, t_n.	Design outside winter air temperature, t_o.	Net energy gain, Btu/hr/sqft due to use of glass.		Glass transmission losses, Btu/hr/sqft.	
				Single glass	Double glass	Single	Double
1. Albany, N. Y.	.483	35.2	—24	—12.9	5.6	108.2	[illegible]
2. Albuquerque, N. M.	.770	47.0	—10	18.05	30.2	90.4	[illegible]
3. Atlanta, Ga.	.522	51.5	—8	9.0	18.8	86.1	[illegible]
4. Baltimore, Md.	.553	43.8	—7	2.0	15.9	87.0	[illegible]
5. Birmingham, Ala.	.510	53.8	—10	10.9	19.5	90.4	48.0
6. Bismarck, N. D.	.546	24.6	—45	—20.1	4.0	129.9	66.0
7. Boise, Id.	.540	45.2	—28	22.9	16.0	110.7	58.8
8. Boston, Mass.	.540	38.1	—18	5.2	11.7	99.44	52.8
9. Burlington, Va.	.419	31.5	—29	—19.5	.9	111.9	58.4
10. Chattanooga, Tenn.	.508	49.8	—10	5.9	16.7	90.4	48.0
11. Cheyenne, Wyo.	.666	41.3	—38	5.7	20.9	122.0	64.8
12. Cleveland, Ohio	.408	37.2	—17	13.7	3.7	98.9	52.8
13. Columbia, S. C.	.511	54.0	—2	11.2	19.6	81.4	43.8
14. Concord, N. H.	.515	33.3	—35	—12.0	7.4	118.6	63.0
15. Dallas, Texas	.470	52.5	—3	7.1	16.4	82.5	43.8
16. Davenport, Iowa	.539	40.0	—27	—3.1	12.8	109.6	58.2
17. Denver, Colo.	.705	38.9	—29	5.2	21.7	111.9	58.4
18. Detroit, Mich.	.429	35.8	—24	14.1	44.0	106.2	56.4
19. Eugene, Ore.	.439	50.2	—4	2.7	13.2	83.6	44.4
20. Harrisburg, Pa.	.495	43.6	—14	—1.5	12.5	94.9	50.4
21. Hartford, Conn.	.532	42.8	—18	—.3	14.1	99.4	52.8
22. Helena, Mont.	.521	40.7	—42	—3.3	12.2	126.6	67.2
23. Huron, S. D.	.579	28.2	—43	—14.1	8.0	127.7	67.8
24. Indianapolis, Ind.	.507	40.3	—25	—4.6	11.2	107.3	57.0
25. Jacksonville, Fla.	.400	62.0	—10	13.9	16.1	67.9	36.0
26. Joliet, Ill.	.530	40.8	—25	2.9	12.8	107.3	57.0
27. Lincoln, Neb.	.614	37.0	—29	—2.2	15.3	67.8	59.4
28. Little Rock, Ark.	.513	51.6	—12	8.5	18.9	92.7	49.2
29. Louisville, Ky.	.514	45.3	—20	1.5	14.6	101.7	54.0
30. Madison, Wis.	.504	37.8	—29	—7.6	9.5	111.9	59.4
31. Minneapolis, Minn.	.527	29.4	—34	—15.74	5.8	117.5	62.4
32. Newark, N. J.	.550	43.4	—13	1.4	15.5	93.8	49.8
33. New Orleans, La.	.370	61.6	7	11.7	16.1	71.2	37.8
34. Phoenix, Ariz.	.590	59.5	16	21.9	27.5	61.0	32.4
35. Portland, Me.	.525	33.8	21	—7.2	12.0	55.4	29.4
36. Providence, R. I.	.542	37.2	—17	—6.1	11.3	98.3	52.2
37. Raleigh, N. C.	.570	50.0	—2	—10.0	20.6	81.4	43.2
38. Reno, Nev.	.637	45.4	—19	8.6	21.7	100.6	53.4
39. Richmond, Va.	.594	47.0	—3	8.0	20.2	82.5	3.8
40. St. Louis, Mo.	.567	43.6	—22	2.6	16.6	104.0	55.2
41. Salt Lake City, Utah	.592	40.0	—20	0.0	15.9	101.7	54.0
42. San Francisco, Cal.	.615	54.2	27	17.3	25.7	48.6	25.8
43. Seattle, Wash.	.340	46.3	3	—7.3	5.2	75.7	40.2
44. Topeka, Kan.	.613	42.3	—25	3.8	18.4	107.3	57.0
45. Tulsa, Okla.	.560	48.2	—16	7.4	19.0	97.2	51.6
46. Vicksburg, Miss.	.447	56.8	—1	—10.7	17.7	80.2	42.6
47. Wheeling, W. Va.	.408	46.1	—18	3.7	9.0	98.4	52.8
48. Wilmington, Del.	.558	45.0	—15	3.7	16.8	96.1	51.0

sol-air temperature

The heat flux, H , into an opaque sunlit surface is

$$H = \alpha I_t + h_o (t_o - t_s) - \epsilon \Delta R$$

H, α, I_t, and t_o have been defined.

- h_o=coefficient of heat transfer by radiation and convection at the outer surface, Btu per degree Fahrenheit per square foot per hour (Btu/°F/ ft²/hr).
- t_s=outdoor surface temperature, degree Fahrenheit (°F).
- ϵ=emittance of the surface, percent. The ratio of the ability of the material to radiate its heat to the ability of a blackbody (ϵ=1) to do the same. (values for some materials are given in Appendix IV)
- ΔR=the difference between the longwave radiation incident on the surface from the sky and the surroundings, and the radiation emitted by a black body at outdoor air temperature, Btu per square foot per hour (Btu/ft²/hr).

The sol-air temperature is an imaginary temperature of the outdoor air which eliminates the radiation terms in the above equation by combining them with the convective term so that the resultant temperature, t_e, is the one that the surface 'sees' because of both convection and radiation. In terms of t_e , H becomes

$$H = h_o (t_e - t_s)$$

and is therefore

$$t_e = t_o + \alpha I_t / h_o - \epsilon \Delta R / h_o$$

Table 25 of the ASHRAE HANDBOOK (HOF - 490) gives sol-air temperatures for July 21 at 40° N latitude. For horizontal surfaces, $\Delta R \approx 20$ Btu/ft²/hr, $\epsilon \approx 1$, and $h_o \approx 3.0$ Btu/°F/ft²/hr; $\epsilon \Delta R / h_o \approx -7$°F. For vertical surfaces, $\epsilon \Delta R / h_o \approx 0$.

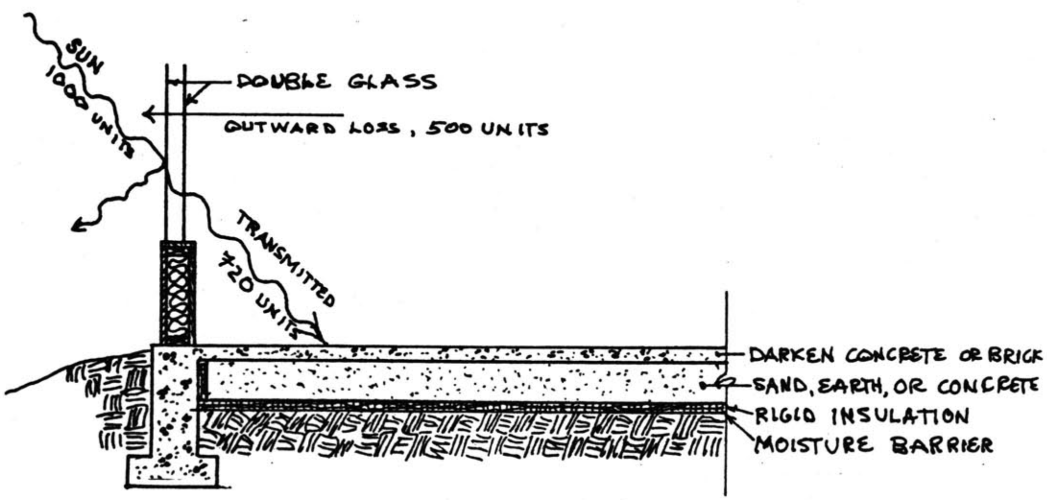
The parameter α/h_o has been given two values; 0.15 is for light-colored surfaces, and 0.30 represents the maximum likely value (for dark surfaces).

For example, at noon, on July 21, when the sun is shining on an average sunny day, 109 Btu are striking a south-facing surface at 40^{o}N latitude. If the air temperature is 90^{o}F and the surface is light in color, the surface 'sees' a sol-air temperature of 112^{o}F.

As with the solar heat gain tables, this table is not a quick useful design tool. Efforts should be made to make it possible, in conjunction with solar heat gain information, for the designer to readily adjust surface orientation, size, color, and composition, knowing the effect of each decision on the heating (or cooling) demand of the interior space.

heat storage capacity of materials

Not much has been written about the role of the total heat capacity of buildings in diminishing the effect of fluctuating outdoor temperatures on indoor temperature and the resultant diminishing heating or cooling demand. We know that heavy stone, earthen, or concrete structures seem cool during warm weather and seem warm during cool weather. One primary cause of this is the thermal heat capacity of materials. An abbreviated explanation of this is that materials absorb and store heat as they increase in temperature, in proportion to the product of their specific heat times their density (see the table). Victor Olgyay in DESIGN WITH CLIMATE describes this phenomenon. Beginning on this page and continuing on the following four pages, are a part of his explanation. (DWC - 115-9) Research and translation of existing information into usable design tools is necessary in order to make this factor part of our design criteria.



(SHH-71)

Table 5 – Comparison of Various Low Cost Materials on an Equal Volume Basis

Material	Specific Heat Btu per Lb per F	Density Lb per Cu Ft	Heat Capacity of One Cu Ft. Btu per Cu Ft per F
Water	1.00	62.5	62.5
Iron, scrap	0.112	489	55
Concrete	0.27	140	38
Brick	0.20	140	28
Magnetite, iron ore	0.165	320	53
Basalt, rocks	0.20	180	36
Marble	0.21	180	38

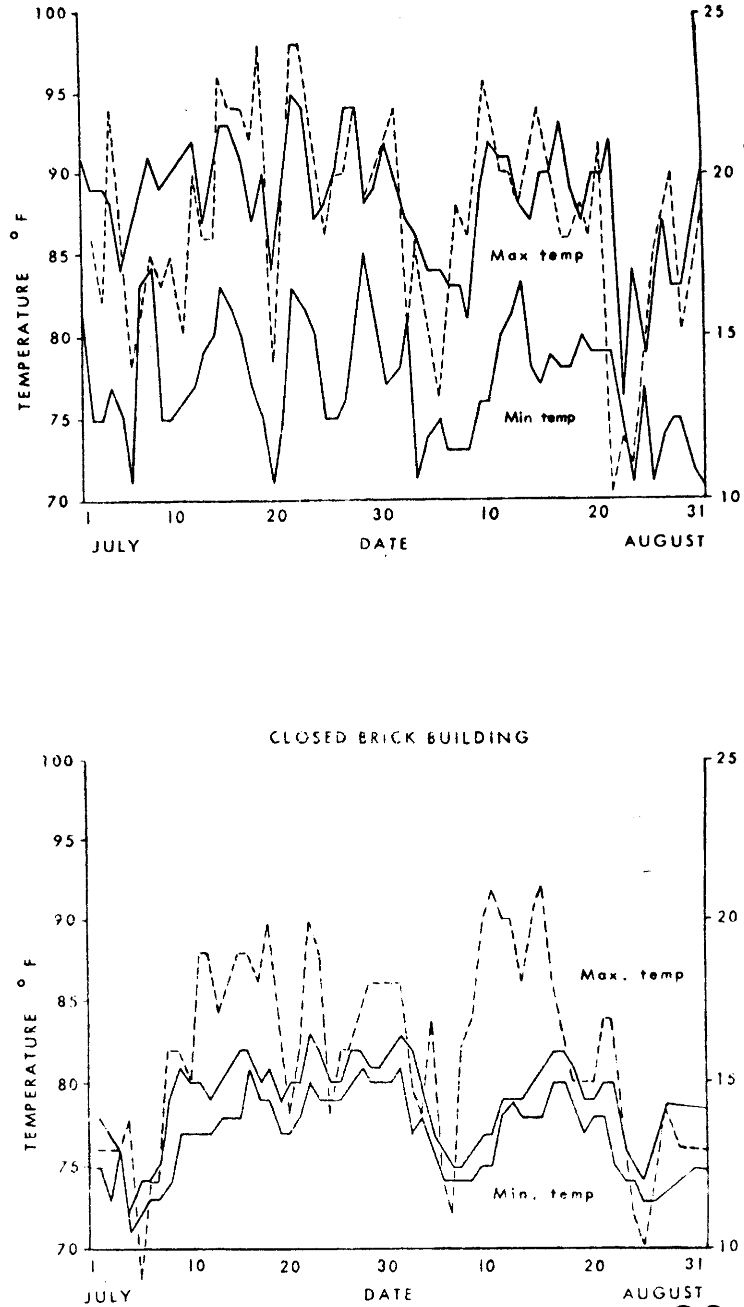
RESISTANCE INSULATION OR HEAT CAPACITY EFFECTS

To evaluate the desirable thermal behavior characteristics for materials in a given climatic region, a study of the yearly temperature conditions with their relation to comfort conditions is needed. From the yearly maximum temperature range a direct relationship can be established to the needed insulation value; and from the daily temperature range a parallel correlation with heat-capacity requirements can be confirmed. On the latter, Leroux[7] recommends that in zones where the diurnal range is 6 to 8° C (11 to 14° F) the construction should be of 300 kg of heavyweight material, such as concrete or masonry, per cubic metre of the building; for a range of 10 to 12° C (18 to 22° F) 600 to 700 kg per cubic metre; and over 20° C (over 36° F) 1200 kg or more per cubic metre. These recommendations, although correct in principle, have been criticized for application in particular.[8] We will offer below a more detailed approach to the problem.

The relationship of comfort conditions and diurnal temperature variation can be illustrated with regard to desirable material characteristics in some typical examples. Heat capacity is essential when the slope of the daily temperature curve (which is equivalent to amplitude) is steep and the resulting flattened daily curve remains in (A), or near (B) in the comfort zone. Where the mean outdoor temperature is expected to be 85° F or higher, heavyweight construction by itself would stabilize temperatures in the discomfort range. However, with steep curves there is the possibility of using low diffusivity materials to absorb the thermal conditions near to comfort situations (C and D), and to maintain them during the extreme periods of the day (with measures such as closing openings to trap shade temperatures or heat peaks).

Both heat capacity and resistance insulation values are required in zones where seasonal and daily variations are excessive (E). Under conditions where the seasonal temperatures are extreme (F) the importance lies in the insulation value, and comfort conditions have to be maintained by mechanical means. Here the daily temperature variation is relatively negligible; however, if it is rather steep, internally placed heat capacity materials can provide a diurnal balancing effect.

Two examples illustrate the marked differences in buildings of different materials under similar conditions. Shown is a comparison between an open, light structure and a heavy, closed one, in locations where the wooden building fluctuates with the ambient outside temperature, reaching 25° daily amplitudes. The closed brick house stabilizes the indoor conditions with low mean temperatures where the maximum diurnal cycle does not exceed 9° variations.[9]



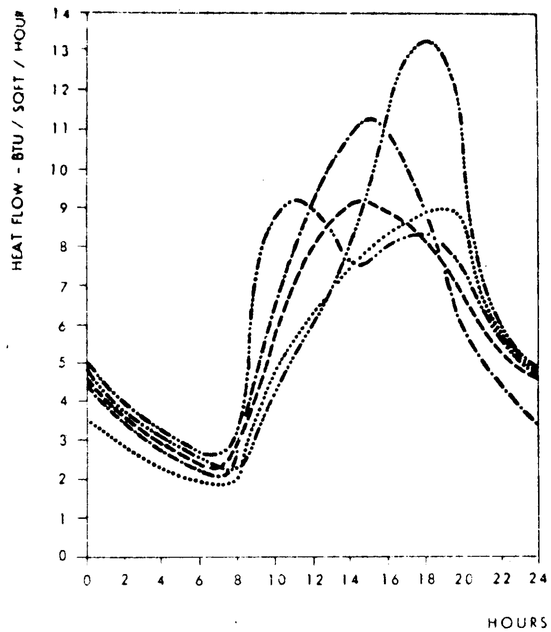
230. Material effects on building behavior.

TIME LAG AND CALCULATION METHODS

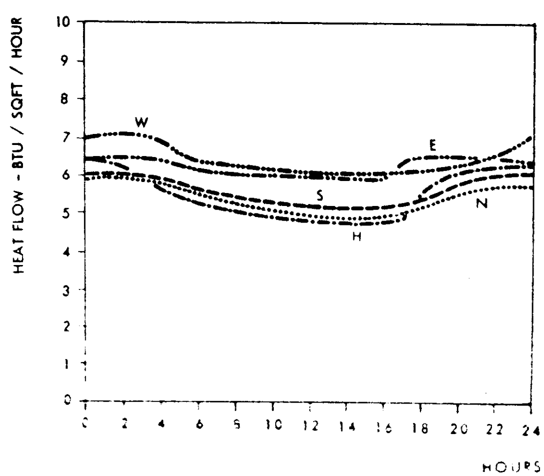
Daily Heat Balance of Structures. In an example a comparison is shown between the behavior of light and heavyweight structures under the same climatic circumstances. The calculations were made for a housing development in Baghdad, Iraq. The upper left graph shows the heat transmission curves for wood construction walls (U = 0.268, lag 2 hrs, color light) under sunlit conditions in midsummer (July 21). The curves on the lower left indicate heat flow behavior of 9″ native Iraq brick walls under the same conditions but with 10 hrs time-lag characteristics. Note that although the total daily heat transmission of the building components at both structures is the same (having equal insulation values), the amplitude and the period of transmission is markedly different. The total daily heat flow behavior of the structures is summarized in the upper right graph; under it the shade-temperature curve illustrates the corresponding outdoor conditions. Note that the light structure heats up during the hot daytime hours (from 7 AM till 7 PM) transmitting 450.5 Btus through the differently oriented unit surfaces, while the heavyweight structure transmits only 331.4 Btus during the same period. Here the heavyweight components are markedly advantageous in the daytime heat balance.

CALCULATION METHOD FOR TIME LAG REQUIREMENTS

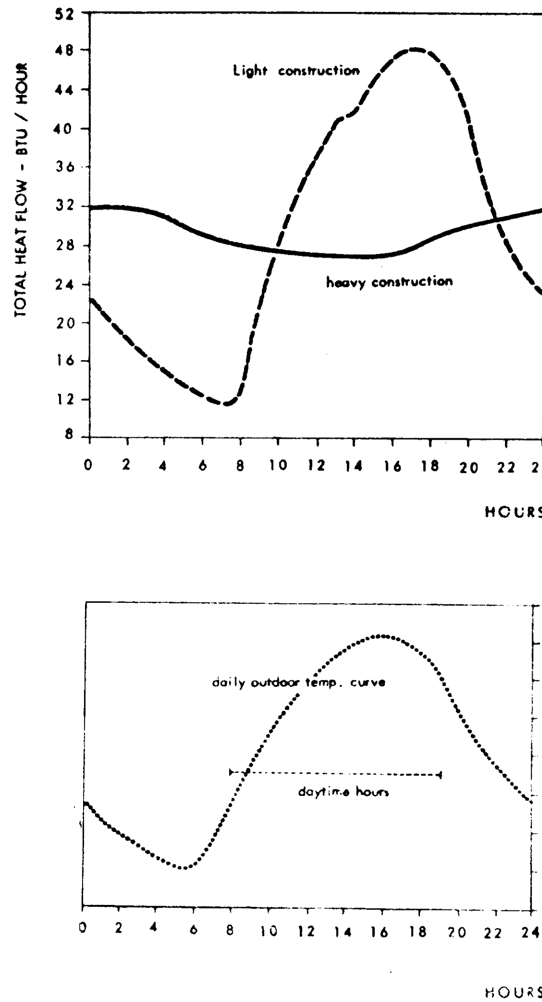
The "shift in phase" effect of capacity insulation provides the leeway to delay outside impacts from heat load periods to a cooler time period and to transmit the nighttime low temperatures to the daytime heat peak. Generally it can be said that in zones of high diurnal



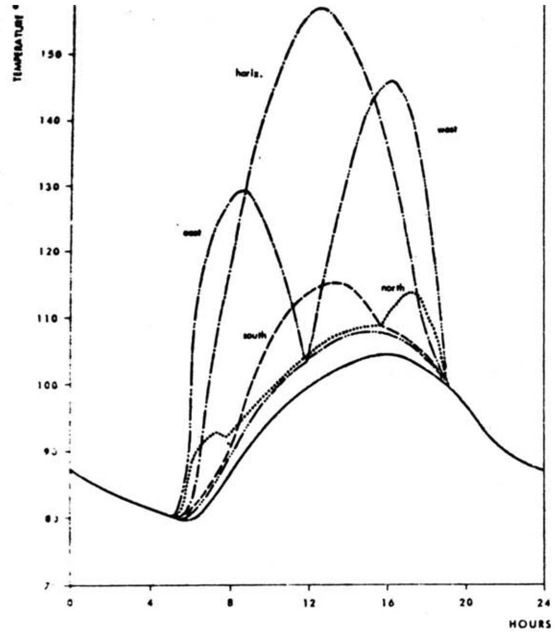
231. Behaviour of light wood structure, Iraq, July.



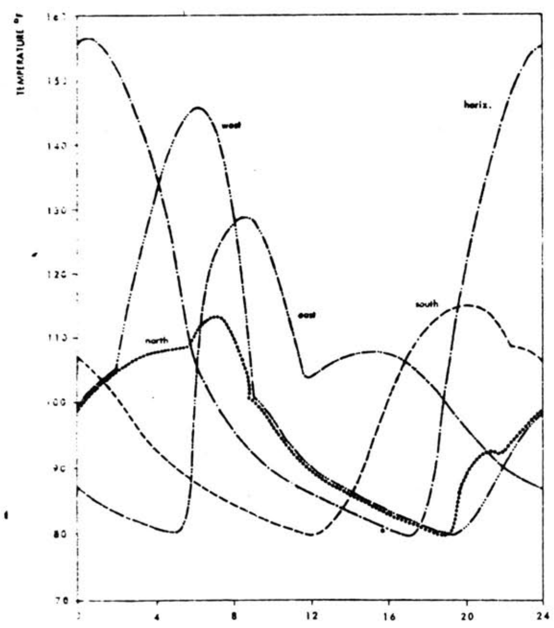
232. Behavior of 9″ brick structure, Iraq, July.



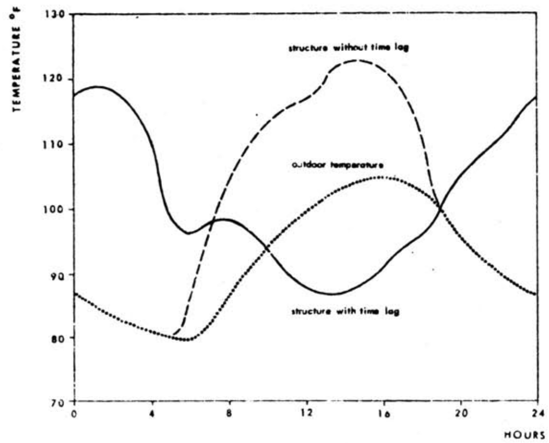
233. Thermal behaviour comparison of the structures, Iraq, July.



234. Sol-air surface temperatures, Phoenix, July.



235. Rearranged sol-air impacts according to desirable time lags, Phoenix, July.



236. Comparison of heat impact on structures with and without use of time lag, Phoenix, July.

variation an approximate half-day time-lag shift (that is, the delay of night coolness to the day and the day warmth to the nighttime) will result in daily thermal balance. However, as the sun's impact heats the various surfaces at different hours, the problem has to be studied in detail.

Such an analysis is applied for Phoenix, Arizona summer conditions (July 21, at clear day, average temperature conditions, $\alpha = 0.7$). The sol-air temperature impacts on the differently oriented surfaces are indicated. Here the accumulated heat load concentrating at the early afternoon hours is evident. In order to shift the impacts to cooler periods different exposures require different time lags. The heaviest load falls on the horizontal surface (roof), needing a shift of 11 to 12 hours. The load on the east exposure would need from a minimum 12 to an optimum 17 hour shift to avoid delivering its heat during peak hours, which indeed would be an extreme requirement. Therefore, the practical solution is to have no lag at all for the east, and to let the impact be felt at the inside while the daytime temperatures are still low. The south side has little importance; the desirable shift is minimum 7 hours, optimum 10 hours. The west side which receives the heaviest load among the wall surfaces should have a minimum lag of 5, an optimum shift of 10 hours. The north wall has the least importance with regard to lag characteristics, however a 5 to 10 hours' delay helps somewhat in the daily heat distribution. The sol-air effect distribution delayed by optimum time lag requirements is shown.

The consequent total heat impacts in a construction unit resulting from the use of optimum time lags are compared with an unbalanced structure. The chart, it should be remembered, is computed with sol-air values excluding the insulation effect of the materials, hence directly applicable only for lag calculations. In the graph the full line indicates the impacts conveyed by the heavy construction, the broken line that of the light structure. The relationship of the curves with the outdoor temperature is illustrated by a dotted line. Note that during all daytime hours (7 AM to 7 PM) the heavy structure will transmit lower temperatures to the interior than the light construction. In the evening, when the light structure cools off, the outdoor temperat struction to utilize ventilative cooling. The graph also indicates that under the analysed comfort conditions the most balanced indoor situation would occur in a house designed so that daytime living areas were built of heavy materials and nighttime areas of light materials.

OVERALL HEAT TRANSMISSION COEFFICIENT (U) AND TIME LAG CHARACTERISTIC DATA FOR HOMOGENEOUS WALLS[10]

Material	Thickness, Inches	U value, Btu/sq ft/hr	Time lag, Hours
Stone	8	0.67	5.5
	12	0.55	8.0
	16	0.47	10.5
	24	0.36	15.5
Solid Concrete	2	0.98	1.1
	4	0.84	2.5
	6	0.74	3.8
	8	0.66	5.1
	12	0.54	7.8
	16	0.46	10.2
Common Brick	4	0.60	2.3
	8	0.41	5.5
	12	0.31	8.5
	16	0.25	12.0
Face Brick	4	0.77	2.4
Wood	½	0.68	0.17
	1	0.48	0.45
	2	0.30	1.3
Insulating Board	½	0.42	0.08
	1	0.26	0.23
	2	0.14	0.77
	4	0.08	2.7
	6	0.05	5.0

In the above table the U value is based upon an outdoor surface conductance of 4.0, and an indoor surface conductance of 1.65 Btu/sq ft/hr. For composite constructions to the individual sums of the time lags an additional estimated lag should be added. It is customary for two layer and light construction walls to add ½ hour more; for three or more layers, or very heavy constructions, one hour additional lag is preferred

The reduction of heat flow is most efficiently achieved by the resistance-insulation property of the material. The desired insulation magnitude is in direct relationship to the difference between outside thermal conditions and comfort requirements. This relationship can be based conveniently on the design temperatures of the locality; and expressed as the "insulation index." However, different exposures, as a result of the sol-air action, have different temperature impacts, diminishing or adding to the thermal heat load. By using "balanced insulation" values to account for these differences, interior thermal conditions may be equalized.

The calculation method for balanced insulation effect is illustrated for four localities. In the middle of the graphs is the plan of a structure. Clockwise at each side the hours of the day are indicated. In the main directions the winter and summer sol-air temperatures are charted on unfolded elevations. The temperature curves, computed for sunny days at average conditions for light surfaces, are related to winter (70°) and summer (74°) comfort conditions. The section of the structure is shown below to indicate roof impacts.

The design condition for each season was selected according to the duration of underheated (when from 7 AM to 7 PM the temperature is mostly under 70°) and overheated days in the year. This underheated versus overheated relationship was found to be: in Minneapolis 75% to 25%, in New York 72% to 28%, in Phoenix 37% to 63%, and in Miami 12% to 88%. Accordingly, in Minneapolis and New York the cold condition (Jan. 21), and in Phoenix and Miami the hot condition (July 21), were selected as design criteria.

The daily temperature fluctuations relative to comfort conditions constitute the main daily deviation from 70° (in winter) or 74° (in summer) gives the measure for relative insulation values in cases where the seasonal impacts impose marked stresses on specific sides, such as the horizontal surface (R = roof) in summer at higher latitudes, the evaluations were calculated on a yearly basis. This results in the following relationships at different exposures:

	E	S	W	N	R
Minneapolis	50†	42†	53†	50†	57*
New York	35†	27†	38†	35†	40*
Phoenix	32‡	28‡	28‡	33‡	45‡
Miami	18‡	13‡	14‡	19‡	30‡

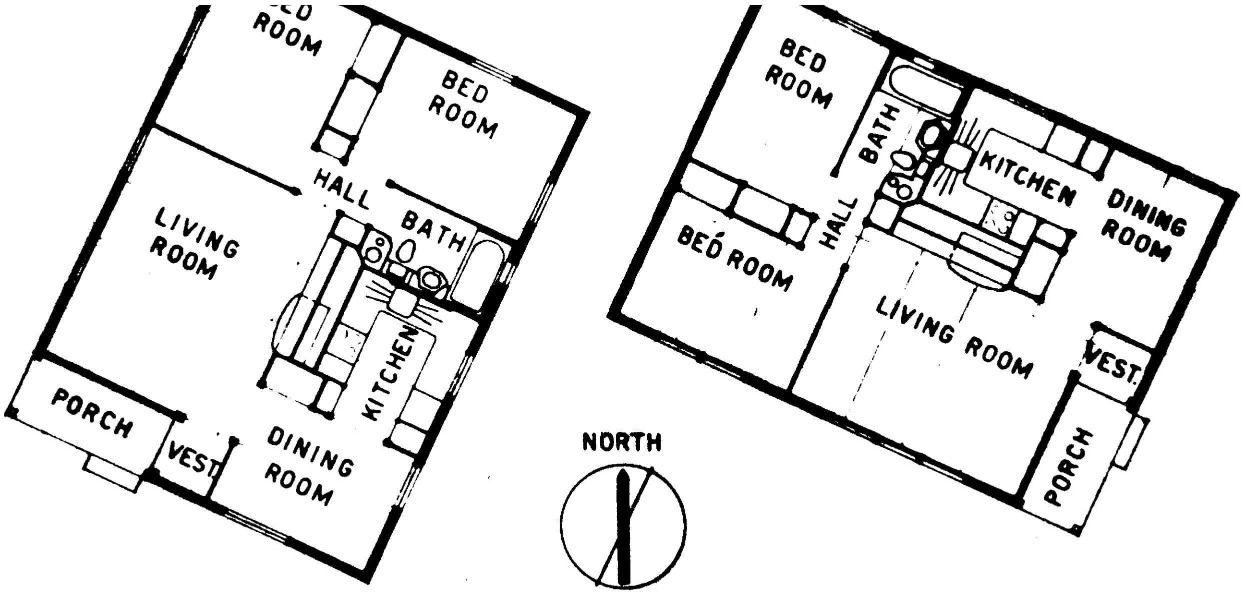
The values marked with † were related to winter loads, those with ‡ to summer loads; values indicated with * were adapted according to the duration and impact both of winter and summer loads.

orientation

Since solar radiation strikes differently oriented surfaces with different degrees of intensity, it follows that a shelter might benefit if its axis were oriented in such a way so as to receive this heat in the winter and shed it in the summer. Henry Niccolls Wright studied this possibility in "Solar Radiation as Related to Summer Cooling and Winter Radiation in Residences". (SRR) His conclusions for New York City are summarized below:

> The maximum heat value of solar radiation is 350 Btu/ft^2.
>
> The maximum heat value of solar radiation is the same throughout the year, probably due to the lower humidity in winter (less atmospheric absorption). Also, the earth is closer to the sun during the winter.
>
> The greatest average heat value reached in winter is in the late afternoon.
>
> "The effective solar radiation on a wall facing south is almost five times as great in the winter as in the summer."
>
> "The effective radiation on a wall facing west-northwest is six times as great in the summer as in the winter."
>
> "The greatest effective solar radiation on vertical walls occurs in the winter."
>
> Therefore, "houses placed broadside to the south-southwest, with most of the important rooms and large windows located on that side - and with a minimum of window area on the west-northest end - will be a great deal easier to cool in the summer, and more pleasant to live in and easier to heat in the winter."

The following two figures (SRR - 5,22) are self-explanatory. In



RESULTS

OLD PLAN:

Original design in worst orientation

HOT IN SUMMER

Sun-heat in Living Room.

MAXIMUM SUN-HEAT:

AVERAGE SUN-HEAT:

COLD IN WINTER

Sun-heat in Living Room.

MAXIMUM SUN-HEAT:

AVERAGE SUN-HEAT:

NEW PLAN:

Revised design in best orientation

COOL IN SUMMER

Sun-heat in Living Room.

MAXIMUM SUN-HEAT:

AVERAGE SUN-HEAT:

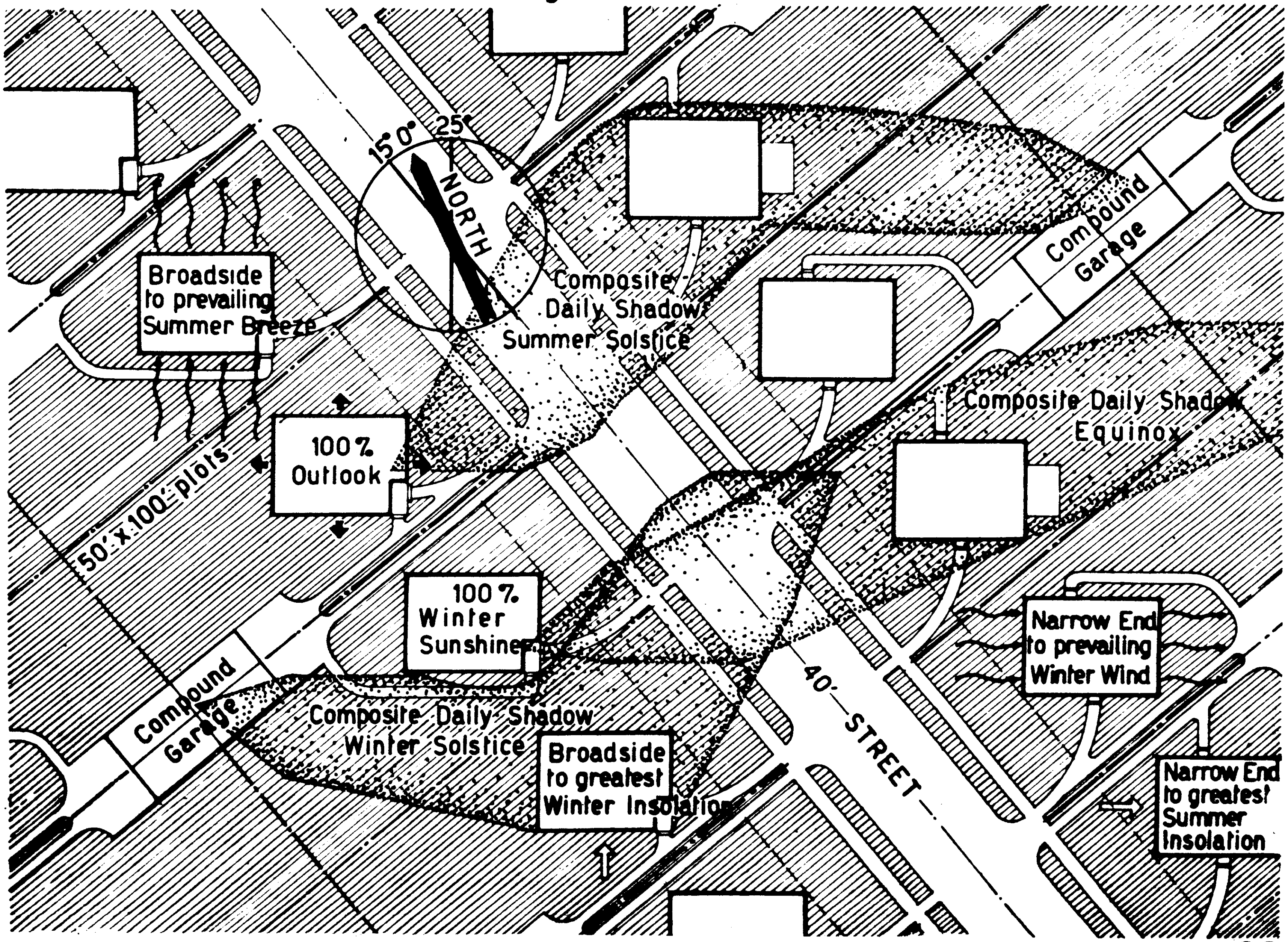
WARM IN WINTER

Sun-heat in Living Room.

MAXIMUM SUN-HEAT

AVERAGE SUN-HEAT

"Heliothermic" Site Planning.



the first, solar radiation on a house of 'worst' orientation is compared with that on one of 'best' orientation. In the second, wind, shadows, view, and insolation are considered in the site planning of 'suburbia' (1930's). Winter winds are minimized and summer winds are maximized. Shadows never hit another house. Orientation takes best advantage of insolation.

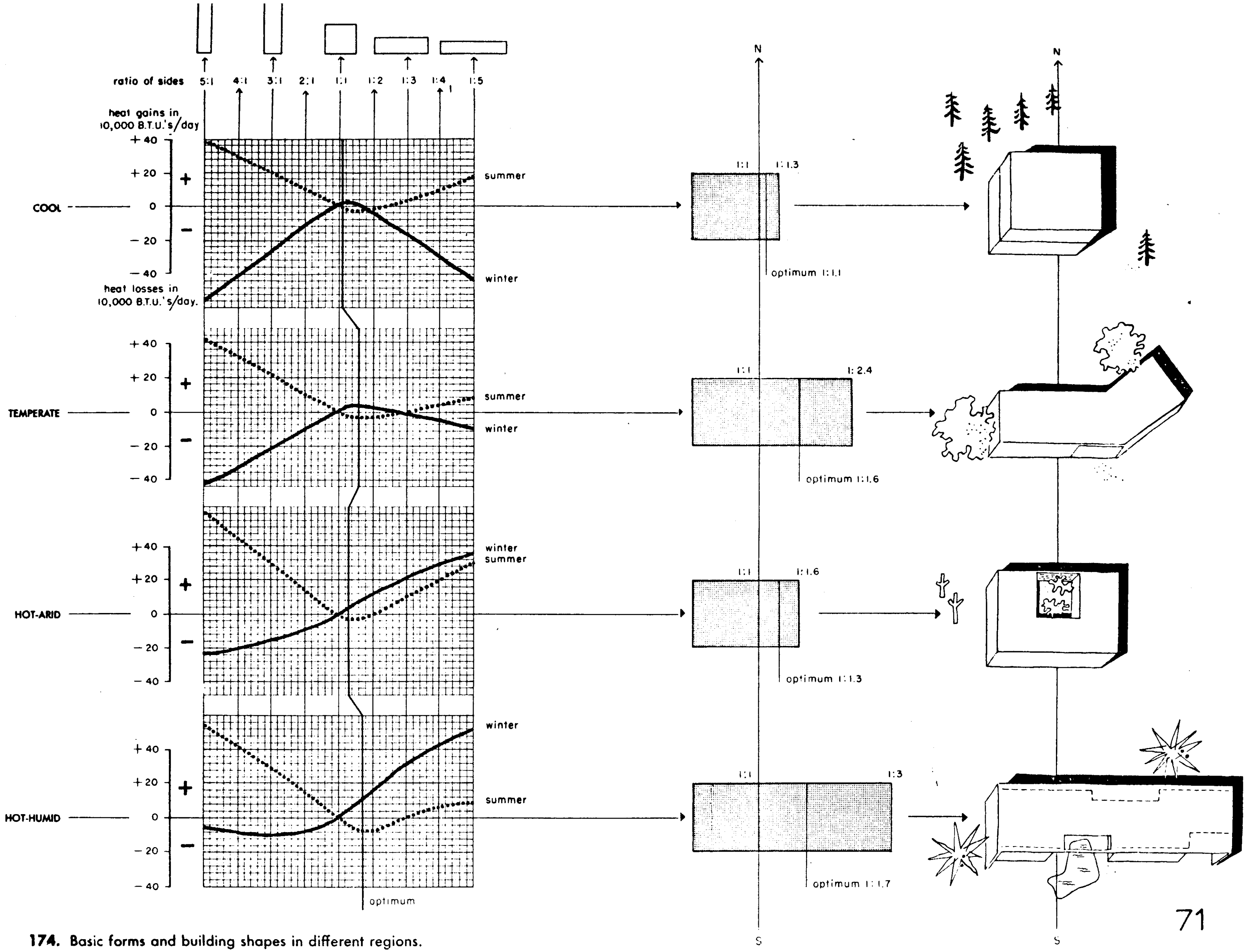
length-width ratios

A shelter benefits in solar heat gain because of its orientation; it also benefits because of different ratios of its length to its width for the same reason. The 'optimum' shape loses the minimum amount of outward moving heat and gains the maximum amount of solar heat in the winter, and accepts the minimum amount of solar heat in the summer. Olgyay (DWC) has shown that

> in the upper latitudes (40°N +), south sides of buildings receive nearly twice as much radiation in winter as in summer. East and west sides receive 2½ times more in summer than in winter.
>
> Lower latitudes (35°N⁻) gain even more on south sides in the winter than in the summer. East and west walls can gain two to three times more heat than the south, in summer.
>
> Well-insulated buildings and those with shading devices show even greater variances but those with small windows or which are shaded show less.
>
> "The square house is not the 'optimum' form in any location."
>
> All shapes elongated on the north-south axis

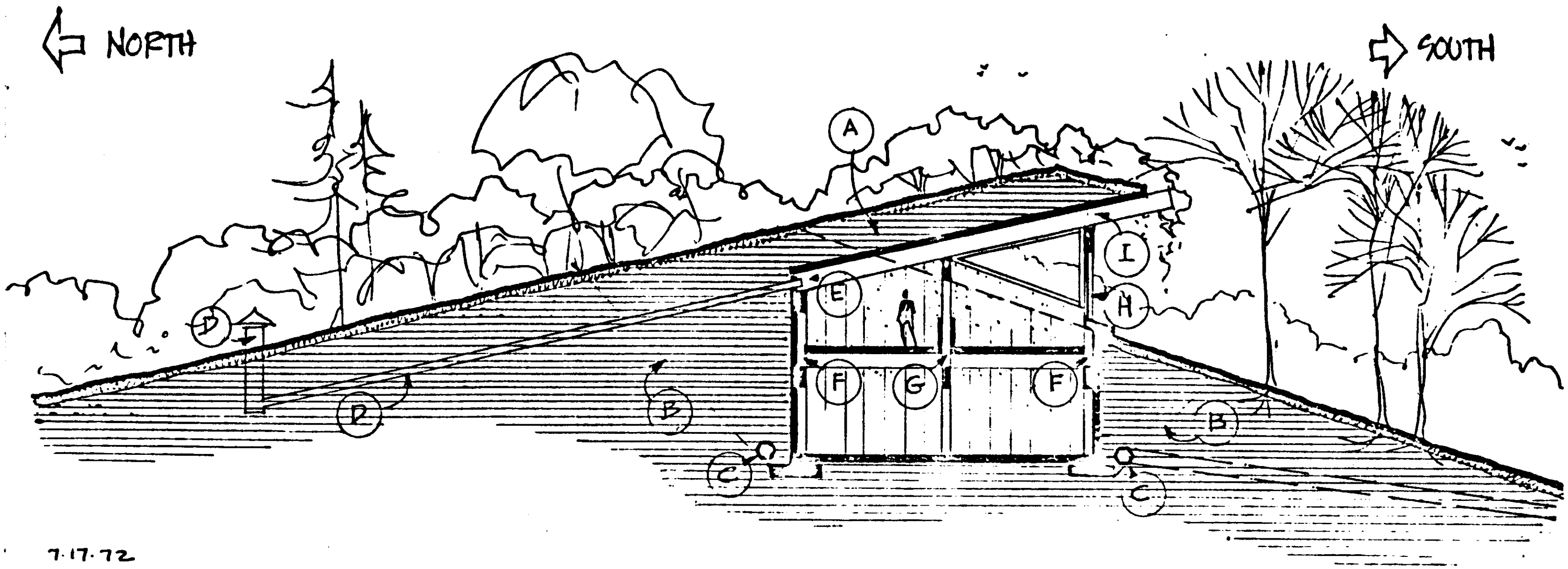
work with less efficiency than the square one in both winter and summer.
The optimum lies in every case in a form elongated along the east-west direction.

The graph on the following page (DWC - 89) shows "basic forms and building shapes in different regions." The four different climates are represented by: cool, Minneapolis, 44°N; temperate, New York-New Jersey, 40°; hot-arid, Phoenix, 32°; hot-humid, Miami, 24°. "Heat gains" represents the Btu impact per day on the four sides and roof of a house as a function of solar radiation and surface temperature, as it affects the heat gain of the interior. "Optimum" ratio (eg, 1:1.1 for 'cool' climates) maximizes benefit from the sun in winter, minimizes it in the summer. "Elasticity" ratio (eg, 1:1.3 for 'cool' climates) shows the "elongated shape that is subjected to the same heat impacts as a square form". (DWC - 88)



174. Basic forms and building shapes in different regions.

an example of putting a lot of these ideas together



7.17.72
DRAWN BY MALCOLM B. WELLS OF MALCOLM B. WELLS PROFESSIONAL ASSOCIATION

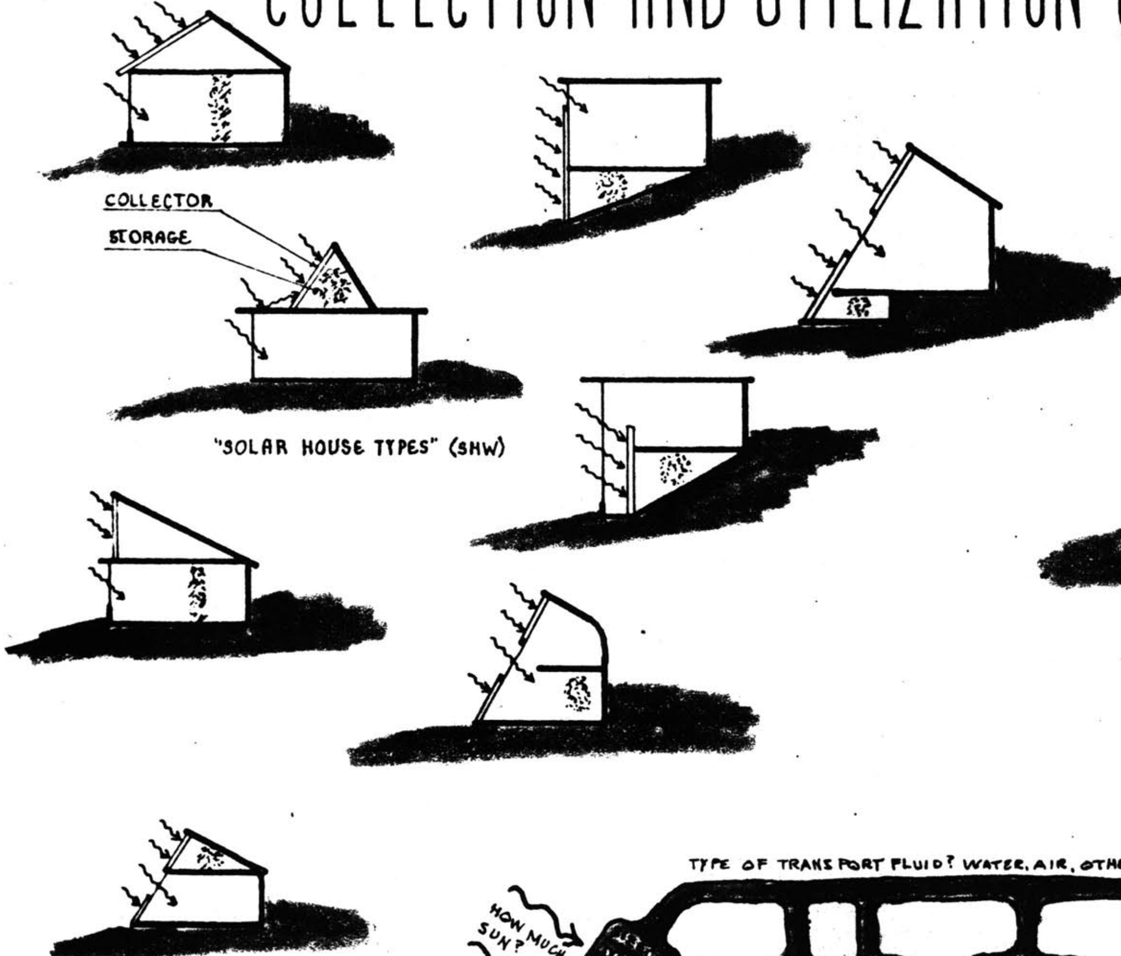
AN EARTH-COOLED, SOLAR-HEATED HOUSE. 1/16" SC. SECTION

A FIREPROOF, EARTH-AND-TREE-COVERED HOUSE BUILT OF STANDARD PRECAST CONCRETE STRUCTURAL MEMBERS, THIS TYPE OF BUILDING IS SAID TO REQUIRE NO MECHANICAL OR ELECTRICAL HEATING OR AIR CONDITIONING! (A SIMPLER, WOOD-FRAME MODEL, BUILT IN THE CAROLINAS, HAD AN INDOOR TEMPERATURE RANGE OF ONLY 15° DURING AN ENTIRE YEAR!)

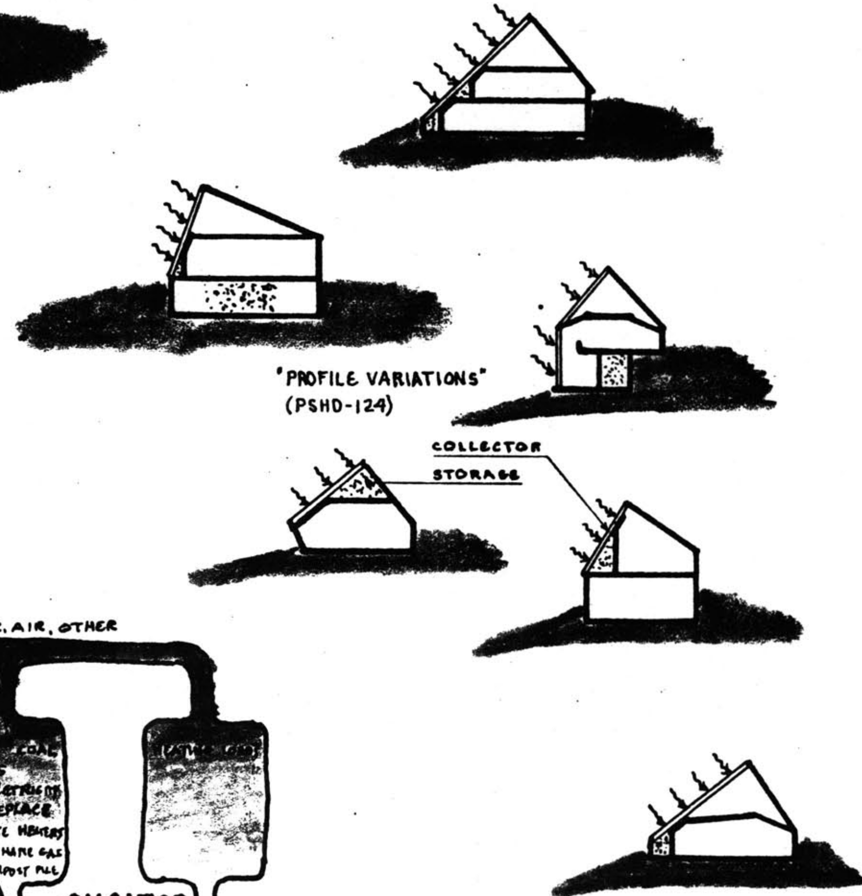
(WINTER) SOLAR HEAT THROUGH LARGE WINDOWS (H) IS SUPPLEMENTED BY EARTH-WARMING OF COLD-WALL AIR WHICH FALLS THROUGH PERIMETER SLOTS (F), IS WARMED, AND RISES THROUGH OPENING (G). MASSIVE INSULATION (A) PREVENTS HEAT LOSS. ((B) SIMPLY INDICATES EXCAVATION.)

(SUMMER) BIG SOUTH-SIDE TREES AND ROOF OVERHANG SHADE GLASS. WARM AIR UNDER ROOF ESCAPES BY GRAVITY AT VENT WINDOWS (I), PULLING IN EARTH-COOLED AIR THROUGH BURIED CONCRETE PIPES (D-E), WHICH CIRCULATES THROUGH HOUSE BEFORE BEING RELEASED AT (I) AS HEATED AIR.

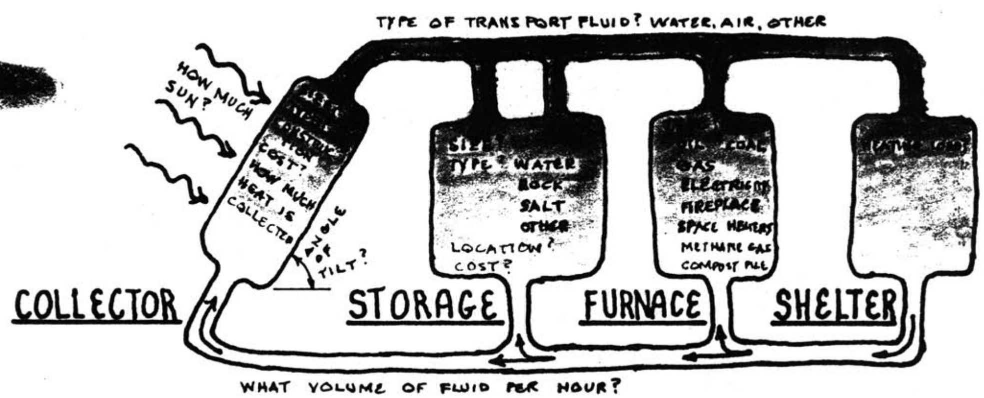
COLLECTION AND UTILIZATION OF SOLAR ENERGY 3



"SOLAR HOUSE TYPES" (SHW)



"PROFILE VARIATIONS" (PSHD-124)



HISTORY

Although lengthy histories of several experimental solar-heated houses are given in Appendix I, the following summary is in order.

The first solar-heated house was built at Massachusetts Institute of Technology in 1939 through a generous donation by Dr. Godfrey L Cabot, MIT '81. The publication by Hottel and Woertz, "The Performance of Flat-Plate Solar-Heat Collectors", is still the basic guide for flat-plate collector design.

MIT's House II tested the notion of combining the operations of heat collection, storage, and delivery to the heated space by exposing a storage 'wall' to the sun. The collected and stored heat was then radiated or convected to the living space. Remodelling of this structure became MIT House III in 1948. The house was successfully heated, largely by solar energy, for several years (a married student and his family lived in it).

Using a slightly different approach to the collection and storage problems (vertical, hot air collectors and salt (heat-of-fusion) storage), Dr. Maria Telkes and two other women completed a solar-heated house in Dover, Massachusetts in 1949. Complications resulted in its conversion to standard heating.

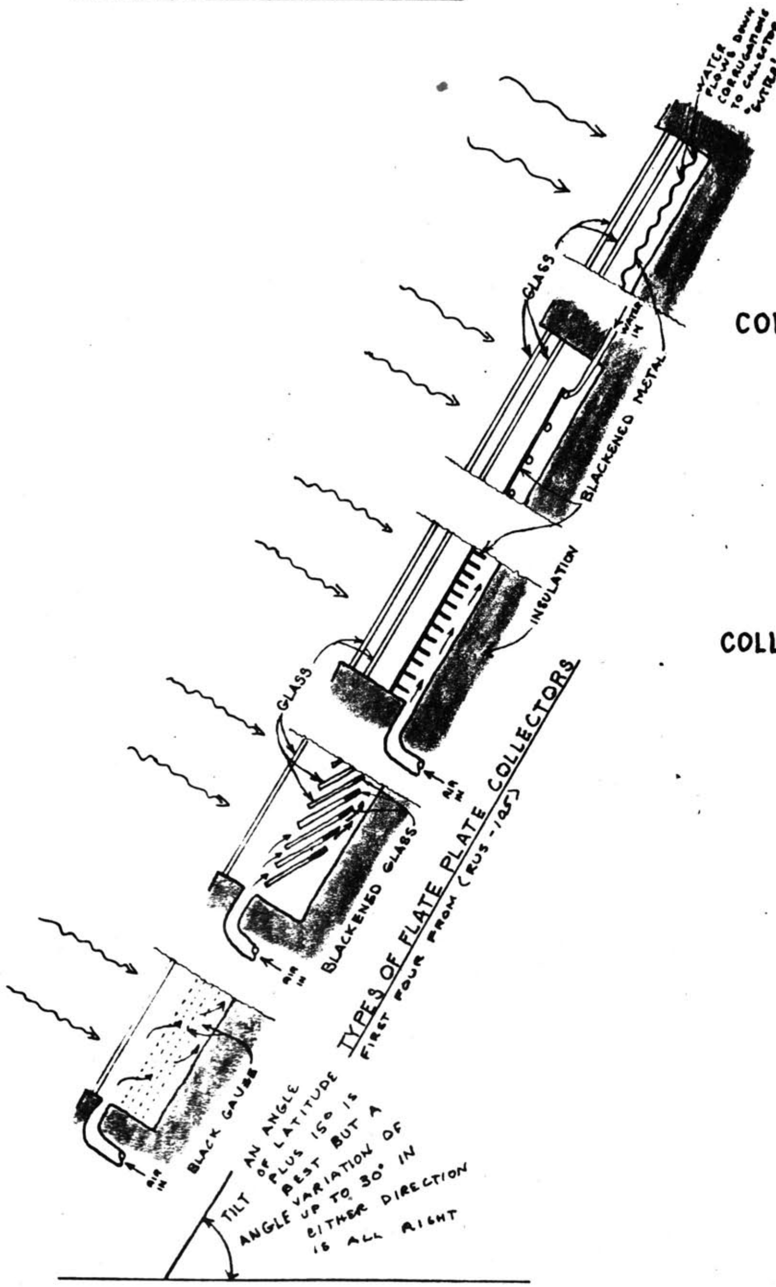
During the fifties, G O G Löf was instrumental in bringing to completion two houses, a small bungalow in Boulder, Colorado and a nine-room contemporary residence in Denver. Dr. Löf explored the concepts of hot air collection, mass-produced collectors, and crushed rock storage.

MIT House IV went into operation in 1959. Its purpose was to make it possible for solar heating to take its place on the American residential scene. It included summer cooling and solar-heated domestic hot water. A series of complications and its economically noncompetitive results led to a halt in MIT's efforts.

Since 1960, Harry Thomason, in Washington DC, has gained a great deal of publicity for his efforts in the development of four solar-heat houses. It appears that his comparative unsophistication has resulted in low-cost collectors, simplification of design, and long-term storage. Few cost figures have been released to the public, however.

A good deal more than these works have been completed, many are now under construction, and others are on the drawing boards, but this summary and the extended summaries in Appendix I may aid in putting present and future work in context. It is hoped that the following pages will help to broaden this context.

ENERGY COLLECTORS



COVERGLASS

- A collector works on the principal of the 'greenhouse effect', that glass is transparent to shorter-wave visible light but is opaque to longer-wave infra red, which is the heat reradiated back from the collector plate.
- One cover glass for warm to hot climates (Phoenix-Miami) and two for cold climates is optimal. Use glass of low iron content.
- Use of plastic in place of glass has been of small success; plastic often becomes brittle and deteriorates; it may also soften at high temperatures. 'U-V'- (ultra violet) treated plastic has a much longer life (up to ten years). Plastic films are cheap, there is a disposal problem, and much plastic is petroleum-based in its composition.
- Construction should be tight enough to keep out dust, rain, and water vapor.
- Efficiency is little affected by dirty glass.

COLLECTOR PLATES

- The absorbing surface, the collector plate, should have high absorptivity (of solar radiation) and low emissivity (will not radiate the heat away but holds it until it is transferred to the collection fluid). Values for absorptivity and emissivity are in Appendix IV. Coatings and surface treatments have been developed (called 'selective surfaces') to improve these properties.
- Usually of blackened (with a matte black paint) aluminum or copper.
- Although lighter than steel and more absorptive, aluminum requires five times more energy in its production and is a scarcer natural resource. (Copper is out of the question) Asphalt and tar might do the job cheaply.

HEAT COLLECTION

- Of the radiation which falls on a collector, about 55% can be collected on clear days, 35% on partly cloudy days, and noe at all on cloudy days. (SH-4) This low efficiency is due primarily to reflection and absorption by the cover glass and reradiation and transmission losses from the collector plate.
- Air or water circulates through the collector only when the collector is 5° hotter than the storage (the energy which is collected must more than balance the energy used to circulate the water or air).
- Efficiency of collection increases with increased difference between storage and collector temperatures.
- Circulation of about 6 pounds of water or 25 pounds of air per hour per square foot of collector is optimal. (PSHD - 124)
- Efficiency of collection increases with increased speed of air or water thru it; the temperature rise of the air or water increases with decreased speed.
- Efficiency decreases with increased difference between outdoor air temperature and collector plate temperature.
- Efficiency is increased with evenness of distribution of collection fluid over the collector plates.

COST

- Approximate cost is $2-5 per square foot (including storage), but this varies greatly with place, people, and conditions. Materials could cost $1.50 or less but are usually around $2.00. Factory production is being investigated as are inflatable plastic collectors.

SIZE

- An approximate size for 30-45°N latitude is one square foot of collector per two square feet of shelter.
- The huge surface imposes severe design constraints.

TYPE

<u>crushed rock</u> or other solids

- inexpensive material
- large but inexpensive storage compartment
- almost maintenance-free
- best for use with a system of using air to remove heat from the collector*
- 1½-3 in-diameter rocks work well, but use all the same size
- stores about 30 Btu per cubic foot for each degree increase in temperature

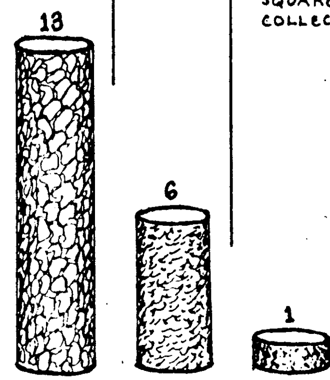
<u>water</u>

- inexpensive material
- fairly expensive cylindrical tank (galvanized steel, extra resistance to corrosion)
- maintenance can be expensive (replacement of tank)
- stores 62 Btu per cubic foot for each degree increase in temperature

<u>Glauber's salts</u> (chemicals)

- not too expensive a material
- unreliable - depends on a phase change from solid to liquid to store heat but stirring is required to reverse the process - this problem remains unsolved
- small volume needed - stores seven times more heat per volume than water (at temeratures around its melting point, 90°F)
- expensive containers

* Thomason uses water as the heat collection fluid, surrounds his water tank with 50 tons of crushed rock, and uses forced warm air to take heat from the storage to the living space.



SIZE

- must be large enough so that the storage temperature is low (to increase the efficiency of the collector). MIT House IV found a storage temerature of 110° to be optimal.
- optimum storage size (based on economics and efficiency) is usually best at from one to three days of cold, cloudy weather. (Thomason has 7-10 days storage - this may be 'economical in his terms.)
- possibly no more than 20 btu per pound of water (about 400 Btu per square foot of collector) can be stored during one day in the winter. (SHSE - 395)

TABLE 4

Sensible Heat Storage Materials

	Specific heat Btu/(lb, °F)	Density lb/ft³	Unit heat capacity Btu/(ft³, °F)	
			No voids	30% voids
Water	1.00	62	62	(62)
Scrap iron	0.112	489	55	38
Magnetite	0.165	320	53	37
Scrap aluminum	0.215	168	36	25
Concrete	0.27	140	38	26
Rock	0.205	180	37	26
Brick	0.2	140	28	20

(SHD - 54)

LOCATION

- locate within the living space - in the basement or attic if necessary but preferably as interior walls, partitions, closets - so that its heat loss will be to the heated interior. Fully insulate storage space, especially between it and the outside. Too little insulation between it and the living space may result in overheating of that space.
- the cost of the solar system might have to include the cost of the space occupied by the storage.
- for a water heat-collection system, locate the storage below the level of the collector to obtain self-draining (so that water won't freeze in the pipes).

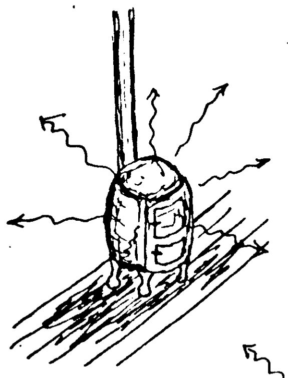
AUXILIARY HEATING

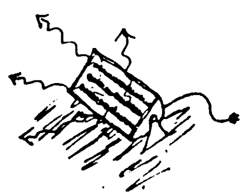
SIZE

The coldest weather may come after a period of sunless days, draining the heat from the storage system. As the cold weather continues, the auxiliary system must be big enough to satisfy the large heating demand resulting from intense cold. The conclusion follows that the solar system is an addition to, and not a replacement for, the traditional heating system.

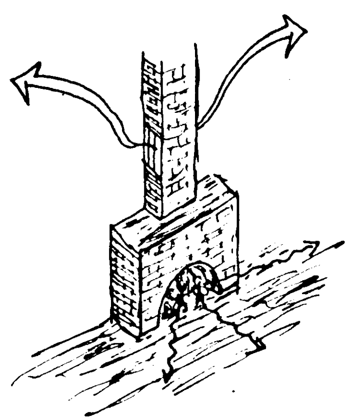
Since extreme cold days and long periods of cloudy weather are occasional, the extra solar energy system (collector and storage) size which would be required for handling these occasions would be expensive for the relatively small amount of fuel saved. Thus there is a need for an auxiliary heating system. (Thomason makes his solar energy system large enough to handle up to 95% of the seasonal demand, but his costs are not known. See Appendix I)

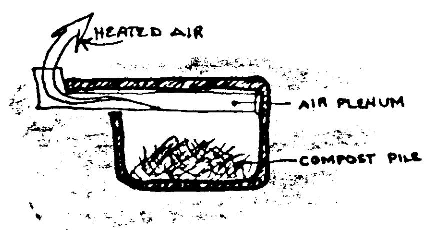
TYPE





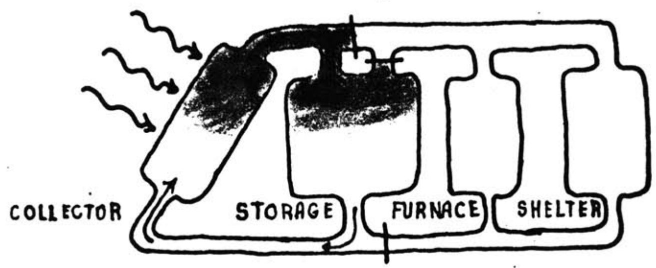
- A traditional furnace should synchronize with the solar energy system so that blowers, coils, piping, ducts or whatever, need not be duplicated.
- The auxiliary heating unit should not heat the solar storage system (PSHD -125) (unless the storage unit is within the confines of the living space).
- A system of forced warm air makes best use of low temperature storage heat.
- The MIT House IV's water-to-air heat exchanger used storage temperatures as low as 84°.
- Forced warm air systems can be used for summer cooling.
- Radiant heating panels have a long time lag (from the switching on of the system to when the heating begins) and need higher operating temperatures (heat from the storage unit therefor is not useful at the lower temperatures that are able to be used by forced warm air systems.
- Heat pumps are being used and investigated as means of making low storage temperatures into useful heat (and for obtaining economic summer cooling from solar heat collection.



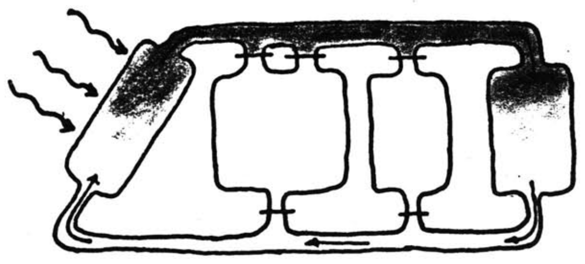


- Since fossil fuels are rapidly depleting in their supply, serious investigation should be made into alternatives to the traditional fossil-fuel-burning furnace. One route might be to leave out a central auxiliary system and instead use a number of smaller local (each room or each section of the shelter) and possibly different types of units: fireplaces, space heaters (electric (occasional use only), wood-burning, methane (home-generated) gas-burning), heat from compost piles.
- Perhaps community centralized heating (and solar collection) is the answer in many situations.

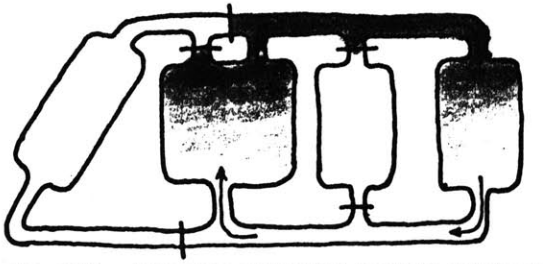
OPERATION



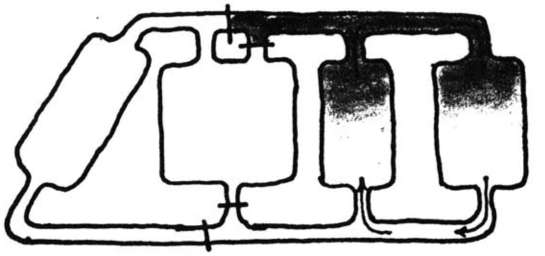
SOLAR SYSTEM COLLECTS AND STORES HEAT; NO HEAT DEMAND FROM SHELTER



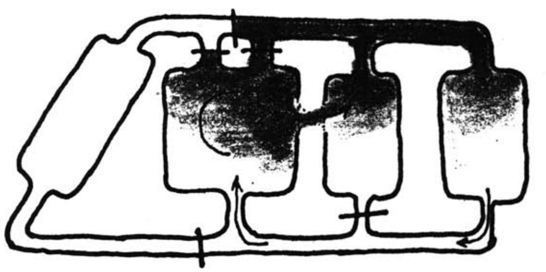
SOLAR SYSTEM COLLECTS ENERGY AND HEATS SHELTER



NO SUN; STORED ENERGY HEATS SHELTER



NO SUN; NO USABLE HEAT LEFT IN STORAGE; FURNACE HEATS SHELTER



NO SUN; FURNACE OR HEAT PUMP RAISES STORAGE TEMPERATURE AND HEATS SHELTER

One of the best summaries of the architectural problems of using solar energy was made in a talk by Lawrence B Anderson, former Dean of the School of Architecture and Planning at MIT, to the World Symposium on Applied Solar Energy at Phoenix in 1955. This and the following page reprint that talk. Most of the issues remain the same today, but some changes and additions may be found on the pages following. (Reprinted from WSO - 201,2)

The Architectural Problem of Solar Collectors—A Roundtable Discussion

LAWRENCE B. ANDERSON
Panel Moderator
Massachusetts Institute of Technology

In order to visualize the architectural problem we must know something about how big collectors have to be, we must appreciate the requirements for angle of tilt, and we must consider the practical aspects of construction and weathering.

How big are flat-plate collectors? If we relied on them as important energy sources, would they become conspicuous in our environment? Here I could make a number of different calculations, with widely varying results, depending on my assumptions. Instead I will simply state this: if you want to build a house in New England, with heat and hot water provided primarily but not entirely by the sun, you will want to design the house so that the sun at noon in winter will not shine on any part of the house except windows and flat-plate collectors. You will need all the heat you can conveniently get. The solution is manageable but the collector is fairly conspicuous.

From this one may deduce that a building in a very cold climate, or in one where there are very cloudy winters, or a building with poor insulation or whose shape is unfavorable might not intercept enough sunshine to take care of its own needs, and might need a collector bigger than its own projection on a plane normal to the sun's rays. Under these conditions the problem becomes unmanageable.

At the other end of the scale where because of clarity of the skies or warmth of the winters, or perhaps because one is trying only to provide domestic hot water or a very little space heating or cooling, there would be situations where the collector becomes a relatively inconspicuous architectural feature, passing, let us say, for a fairly large skylight.

Size depends on how much energy you are trying to obtain. The roof of the new unit described by Dr. Daniels*, at 5 percent efficiency would furnish 28 kwhr per day. On the present U. S. scale of consumption the *total* energy needs are such that per family one would require one half-acre of collector area or 20,000 sq. feet, at least ten times the floor area of the average house. There are other uses for the land, too; it would be a mistake to cut all the trees to avoid shading the collector. One half-acre of land per family corresponds to a fairly sparse suburban housing density.

If the answer to the area question is that the collector area for space heating tends to be of the same order of magnitude as area of south-facing house envelope, what about angle of tilt? Ideal tilt, or angle from the horizontal, is the same as latitude for maximum twelve-month incidence, 15 to 20 degrees greater than latitude for winter optimum; correspondingly less than latitude for summer optimum. How do these angles relate to the traditional elements of building enclosure? I remind you that the building techniques of most countries have seemingly settled on a class of elements called walls that are ordinarily vertical and another class called roofs that vary from the completely horizontal to a maximum tilt of about 45 degrees from the horizontal. Optimum tilt for shingle materials appears to be 25 degrees or so.

Vertical south-facing (or in southern latitudes north-facing) walls have limited applicability for solar-energy collection. Their interception is substantially less than that of collectors of optimum tilt. Considering winter conditions only, it would be only in Canadian or better latitudes that vertical walls could hold their own. For summer collection of solar energy or for any collection in latitudes

*Dr. Daniels' paper is presented on pages 19 to 26.

less than about 45 degrees, the vertical wall is substantially less than the best.

Roofs, whether flat or gently tilted, also have limitations. Solar collection in the tropics or the subtropics where the sun is much nearer the zenith can use the roof to advantage. In these climatic regions, the need for space heating is much diminished or even non-existent. Domestic energy needs under these conditions will be dominated by the domestic hot-water load, or perhaps if the standard of living is high, by the hot season energy demand of the mechanical cooling devices. This puts the emphasis on the summer season for maximum collection needs, and tends to make the collector flatter and more rooflike. It is easy to imagine a rather effortless adaptation of building techniques to solar-energy collection in the warm regions, thinking in terms of skylight-resembling units mounted on flat roofs or of south-facing roof slopes of very conventional pitch. Where the interiors of houses are not maintained warmer than the exterior ambient temperature, there is no great advantage to having collector surfaces designed as part of the house envelope. Collectors intended to provide energy only for domestic hot water or for space cooling might better be garden or terrace features.

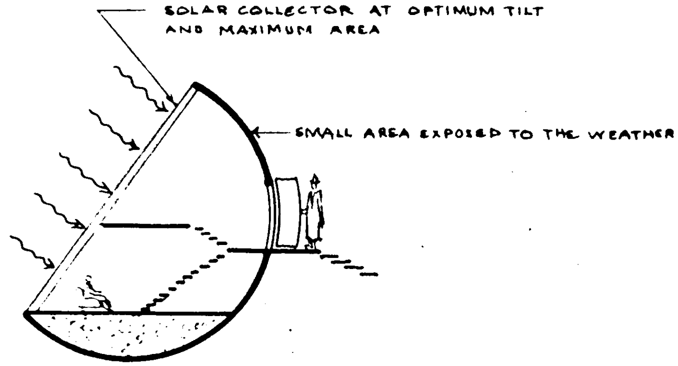
The architectural problem of the flat-plate collector is much the most acute in the temperate zones, the latitudes 35 to 55 degrees, where one would like to use a collecting surface tilted at a mansardian angle that is classifiable hardly as wall or as roof, and having an area big enough to intercept most of the energy falling on the house at midday in November to January. This poses a severe limitation on the designer and will produce buildings that differ substantially in appearance from the forms to which we are accustomed. The collector that works in the winter time, in a latitude where winter days are short, and especially where many days are cloudy, finds itself in competition for space with the south-oriented window. The collector puts away sensible heat for use at night or on cloudy days: the window offers instantaneous energy consumption only, but this is consumption accompanied by spectacular and psychologically irreplaceable visual stimulation. It is hard indeed to make a fair allocation of the available radiation when intangibles are on one side of the scale.

On the whole this temperate-zone collector design situation, while a stimulating challenge to the architect, interesting as an exceptional and occasional case, would be prohibitively restrictive if it had to be applied to all construction in these regions. It would limit urban densities and put building design on very difficult geometric discipline. I am inclined to say that existing urbanized and industrialized cultures would have a hard time indeed to make a total adaptation. First values will probably appear in the more manageable subtropics, with occasional brilliant contributions in the sunnier climates of other latitudes.

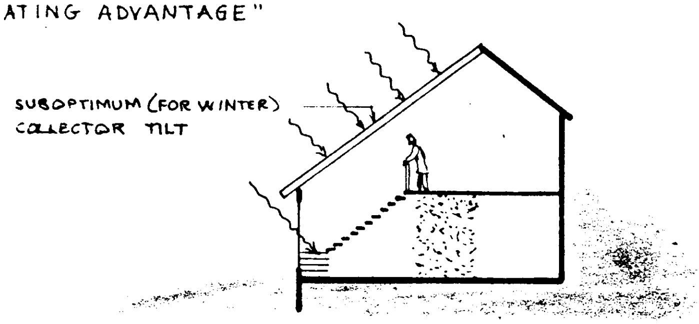
We have considered the area aspect and the tilt aspect of collector design. We need also to mention the technical problems of construction. As a rough approximation, if a square foot of collector in Massachusetts will collect and store during one heating season no more than the equivalent of one gallon of fuel oil, it is important to build collectors cheaply. But collectors are relatively complex building elements, having in most cases more than one transparent layer backed by a blackened surface, equipped with passages for air or a liquid to carry off heat, and heavily back-insulated. The outer layers must be as transparent to solar-energy wavelengths as possible, but must remain impervious to the edge leakage of water and dust through temperature gradients of up to 200 degrees F, while presenting themselves to the elements at highly vulnerable angles. They must be capable of keeping these characteristics for a period of years.

Glass seems to be today's best material for these transparent layers, but it is by no means easy to find the material and the technique with which to do the edge sealing cheaply and dependably. Glass itself is an industrial material, cheap in mass production, but it is heavy, fragile, and inflexible. In transportation it imposes problems of handling to avoid breakage. With prefabrication there is always the dilemma: whether to put the glass into the components in the factory under controlled conditions, or to plan this work for less desirable field operation in order to make transportation more compact and less hazardous in terms of breakage.

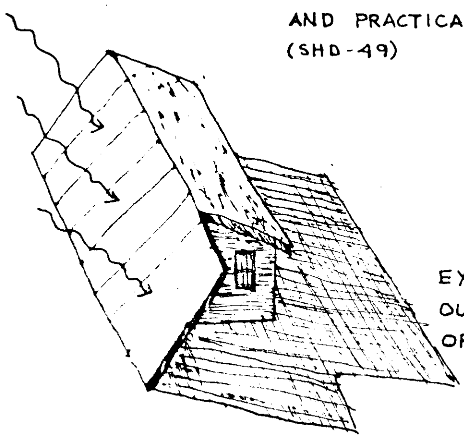
If we are trying to provide for the utilization of solar energy in areas of the world where it is inconvenient or expensive to transport conventional fuels, the need to use glass may tend to defeat our objective unless it is plentiful locally or can be made so. What is the ideal structure and material for a solar collector? If plastics were really cheap, if they were transparent to solar energy, and if they would not deteriorate when exposed to ultra-violet radiation, it is possible to imagine a multilayer structure composed of thin, flexible films cemented together so as to form air spaces and tubes, a central layer being pigmented, which would be the complete collector—front and back insulation, black plate, and fluid transport all in one. This quilt could be collapsed and rolled for shipment. Some day such a structure may be available.



"HYPOTHETICAL DISPOSITION FOR MAXIMUM SOLAR HEATING ADVANTAGE" (SHD - 49)



"A COMPROMISE WITH CONVENTION AND PRACTICALITY OF CONSTRUCTION" (SHD - 49)



EXTEND COLLECTOR OUT BEYOND EDGE OF SHELTER

collector size and shelter design

The enormous square footage of the required collector surface (300-1200 ft^2) is the primary difficulty in the incorporation of a solar energy system into the design of a shelter. This page and the first page of this section show a large number of variations on the same themes:

- minimum exterior surface area per inside volume to decrease heat loss;
- optimum length-width ratio to take maximum advantage of the sun (discussed in section two);
- incorporation of the maximum square footage of collector surface possible into the south-facing facade, trying also to include windows.

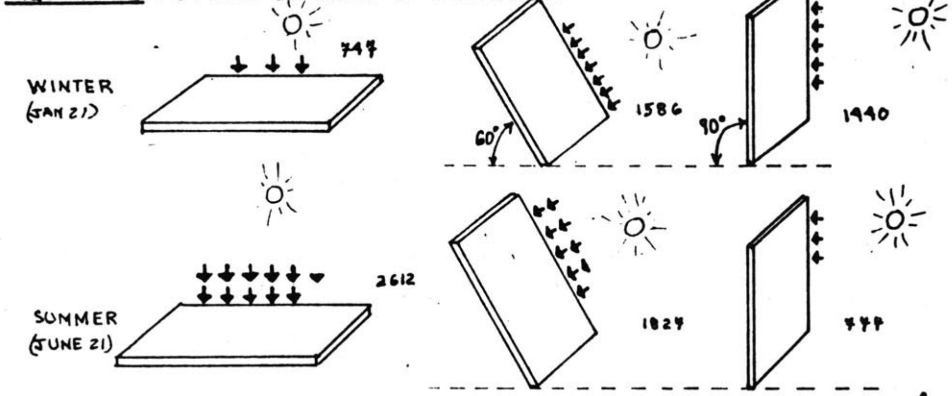
The main arguments for including the collectors as part of the shelter's envelope are:

- The living space gains some of the heat from the back side of the collector.
- The collector (plus normal roof insulation) make an excellent insulative exterior wall/roof. It may have a U -value of 0.03 Btu/°F/ft^2/hr as compared with 0.07 for the usual roof (MIT House IV (WSO - 118)).
- The effective cost of the collector is less if it uses the structure of the shelter as its foundation and replaces the expense of what would otherwise be a roof.

The main arguments against integrating collectors into the shelter's facade are:

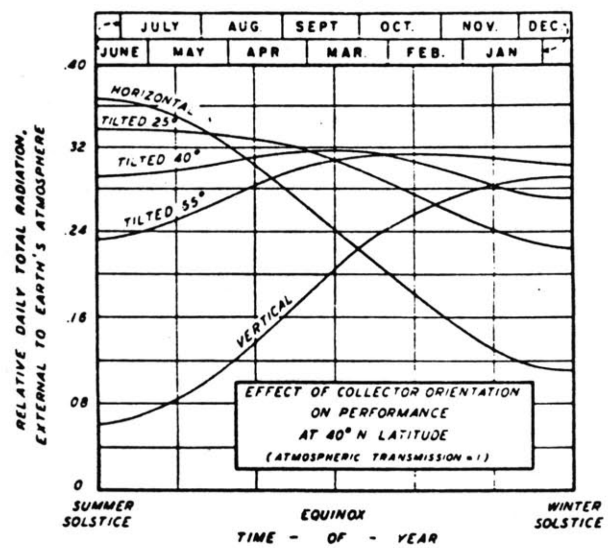
- It imposes a difficult architectural constraint: a large expanse of glass facing south at a certain angle.
- Its use may not allow south-facing windows, which may then result in more windows on the east, west, and north walls, increasing the heat loss of the shelter.
- The collector is stationary and cannot change orientation to follow the sun.
- It does not allow natural solar heat gain on the south exposure of the shelter.
- It requires expert construction.

TILT ANGLE AS MEASURED FROM THE HORIZONTAL



FROM FIGURE 2 (SHPH): "AMOUNT OF TOTAL RADIATION FOR CLEAR-SKY CONDITIONS ON A SOUTH-FACING SURFACE, WITH VARIOUS INCLINATIONS, IN THE NEW YORK-NEW JERSEY AREA. EACH ARROW REPRESENTS 250 Btu/ft²/DAY." **1**

FROM FIGURE 2 (RUS-105): "IDEALIZED EFFECT OF COLLECTOR ORIENTATION ON PERFORMANCE AT 40 DEGREES LATITUDE." **2**

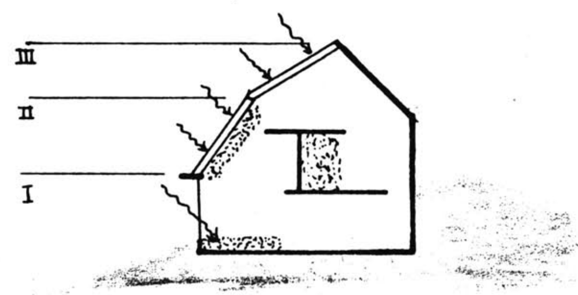


tilt angle and shelter design

The optimum tilt angle is usually given as the sum of the latitude plus 15°, so that the collector is perpendicular to the sun's rays in the middle or end of January, the coldest days. Viewing the architectural solutions on the first page of this section and of the work of most researchers in the field, the tilt angle used has usually been the optimum one. From figures 1 and 2, it is apparent that a vertical face receives within 90% of the radiation which an optimally angled (50-60°) surface would receive. Over the course of the heating season, however, the variation between the two surfaces is a bit more, perhaps an 85% figure instead of 90%.

To go to a tilt angle of 25° would result in nearly the same collection for the season as the vertical collector, and nearly the same collection in March as the optimum (55°). But in January it collects about 80% of the optimum (the 40° tile does closer to 92%).

Hottel describes figure 2 as the "idealized effect of collector orientation on performance at 40°N", so a tilt angle ranging from 25° to 90° with only a 20% variation in heat collection as shown is probably not "realistic" because of other factors affecting efficiency, but it is clear that we should be willing to use that range in design work. Tradeoffs are involved of course, but cost and fuel savings are not the only factors affecting design decisions. The "Range of Tilt Angle" is further shown in Appendix VI.

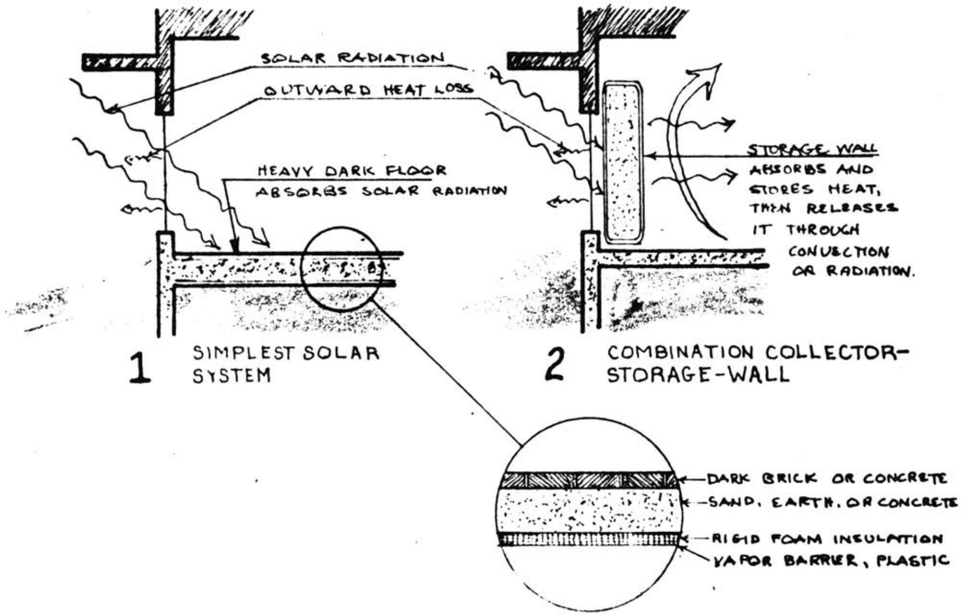


THREE ZONES OF HEAT COLLECTION

I. PRIMARILY WINDOWS WITH SHADING, CURTAINS, SHUTTERS - SOME SOLAR COLLECTOR SURFACE

II. OPTIMUM ANGLE FOR WINTER COLLECTION, (LATITUDE + 15°); COMBINATION OF COLLECTORS AND WINDOWS - SOME HEAT STORAGE IN WALLS.

III. OPTIMUM ANGLE FOR SUMMER COLLECTION (LATITUDE - 15°); MOSTLY COLLECTOR SURFACE BUT SOME WINDOWS.



1 SIMPLEST SOLAR SYSTEM

2 COMBINATION COLLECTOR-STORAGE-WALL

heat storage and shelter design

The three primary concerns - size, type, and location - were outlined on the page HEAT STORAGE. The basic information for consideration of its incorporation into the shelter is:

> Chemical salts take up the least space (but are unreliable); The cost is basically in the small, individual containers.
>
> Water is a cheap material. It normally requires about 1500 gal (200 ft^3 plus insulation and access); the corrosion-resistant tank is the main expense and will need replacing.
>
> Crushed rock is a cheap material (especially if collected by hand) and requires no maintenance; the main expense is in providing the large storage space, two to five times as large as that needed for water.

Figures 1 and 2 show the most basic forms of collection and storage and can be included as parts of the total system. Figure 3 charts the relative efficiencies of the three types.

No matter how well insulated it is, the storage tank will lose heat. If it must be exposed to the exterior of the shelter, massively insulate that interface. The report of the MIT House IV (Appendix I) showed that during January 1960, total solar collection came to 7.4 million Btu, of which 1.3 million was lost from the storage tank - good reason for making sure that it is within the living space. This can be done in many ways, two of which are shown above. If the storage is a water tank, it can be placed within a large closet in the living space (on a strong floor). Large volumes of rock are another matter. Löf has contained them in large vertical cylinders within his space. Thomason put them in a crawl space. (Appendix I)

Better insulation of the storage decreases the need for its placement within the living space. If the MIT tank had been insulated to the equivalent of two inches of polyurethane (thermal resistance, R, = 15), the heat loss would have been less than half. A following page, LONG TERM STORAGE, discusses a water tank 20 feet long and 20 feet in diameter for collecting summer heat for winter use. This possibility should be carefully studied.

3 (SHH - 70)

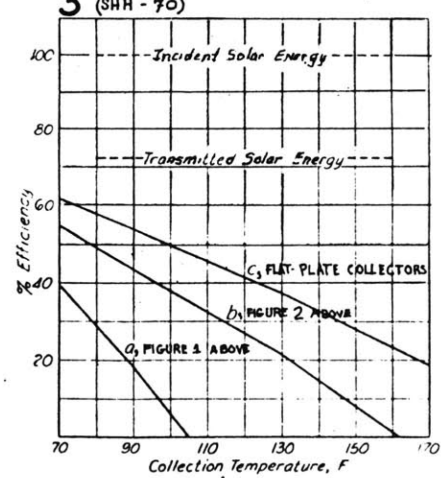
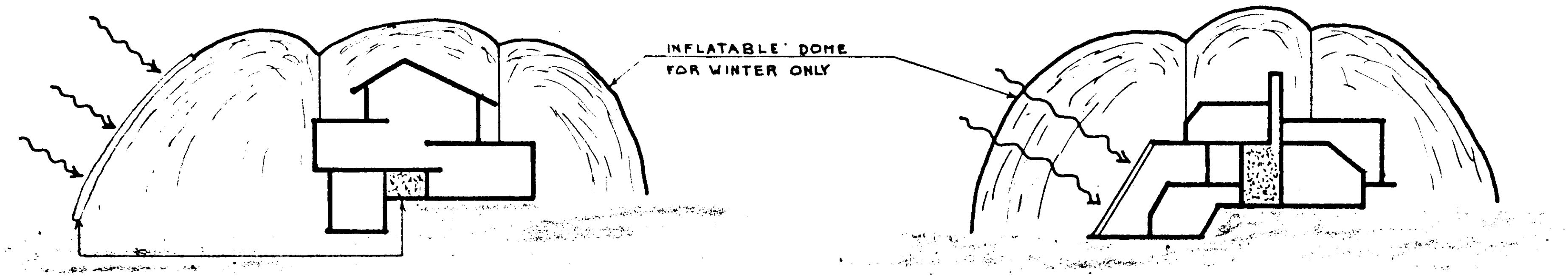
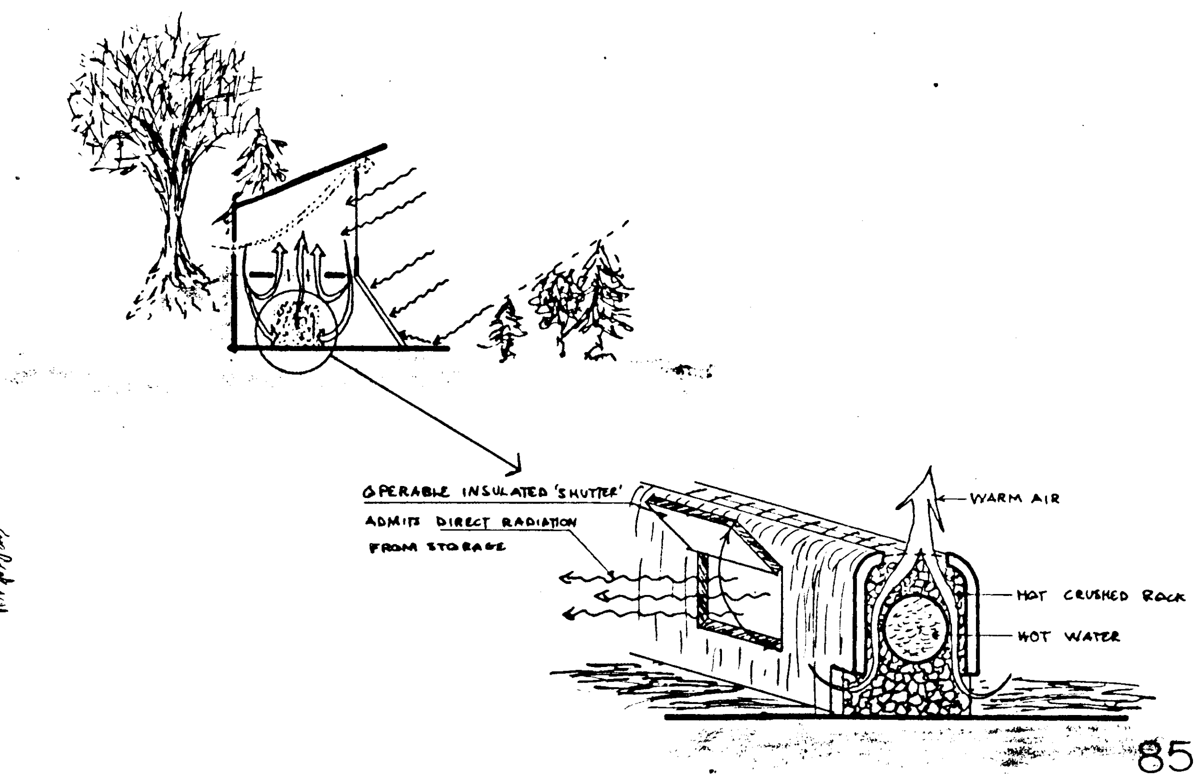
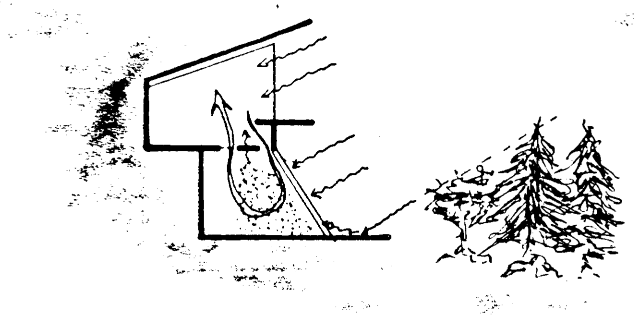


Fig. 3. Calculated efficiency of south facing vertical solar energy collectors, at Blue Hill, using two glass plates.

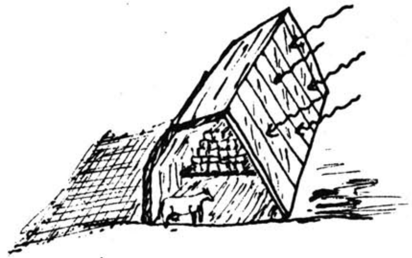
Dec.-Jan. average outdoor temperature, 30F. Solar energy on clear days is 1500 Btu per sq ft per day. Outdoor losses—a, 24 hr; b, 8 hr, diminished loss 16 hr; c, 8 hr, no loss 16 hr.

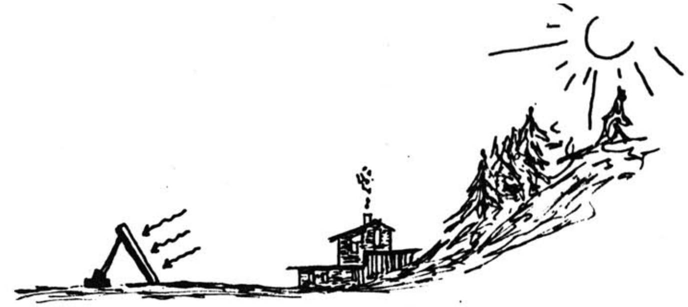

INFLATABLE' DOME
FOR WINTER ONLY


OPERABLE INSULATED 'SHUTTER'
ADMITS DIRECT RADIATION
FROM STORAGE
WARM AIR
HOT CRUSHED ROCK
HOT WATER



A SEPARATED COLLECTOR





CONSIDERATIONS IN USING A COLLECTOR SEPARATED FROM THE SHELTER

INITIAL COST

EXTRA COSTS

- construction of roof or wall of the shelter which collector would have replaced. If owner-built, figure only the cost of materials.
- foundation and structure for the separated collector, the major increased expense. Cost varies greatly with range of the adjustment of orientation and tilt angle. No or little extra cost if part of a barn or shed.
- increased mechanical runs from collector to storage: piping, insulation, burying.

SAVINGS

- less precision needed for the framing of the shelter
- construction of collector can be easier, less water-tight, if it is not acting as a roof.
- collectors may take on new designs if not a part of a shelter's skin (inflatables, focusing collectors, etc), resulting in possible savings.

FUEL COSTS

EXTRA COSTS

- collector no longer loses some of its heat to the interior space.
- collector no longer adds to the insulative value of the facade.
- there is extra loss of heat thru the mechanical runs from the collector to the shelter.

SAVINGS

- allows solar heat gain through south-facing windows, walls, and roofs of the shelter.
- adjustable orientation and tilt angle of a separated collector results in higher efficiency.
- new designs made possible by the separation from the shelter may mean higher efficiencies.

DESIGN VALUES

SAVINGS

- allows usual design freedom of the shelter.
- collectors could still be a part of the south-facing facade, but a smaller part.
- the collector can be made larger.
- a separated collector can be built after (or before) the shelter is built.

EXAMPLES

1) → The owner does none of the work to build
→ an adjustable (orientation and tilt angle) separated collector.

All of the extra costs and extra savings apply to this situation. The figuring of economics is difficult at best but design considerations alone may swing the balance to the separated collector.

2) → The owner does the work of building
→ an adjustable separated collector.

The owner figures economics anyway he likes, but will probably find a separated collector economical if he doesn't figure labor costs. He may be more inclined to heavily weigh the ecological considerations of fossil fuel savings and decreased pollution which result from his collector's larger heat collection capacity.

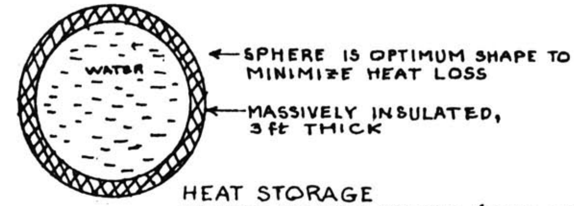
3) → The owner does the work of building
→ a collector on the south-facing wall or roof of a barn or shed or other auxiliary building.

The costs are similar to building the collector onto the shelter. The main increased costs are the longer mechanical runs from the collector to the shelter, both in their initial cost and in their heat losses. The main savings is in the solar heat gain of the south-facing facade of the shelter, and of course in the design freedom.

LONG-TERM STORAGE

H C Hottel of MIT reported (RUS - 107) that an analysis of a single dwelling in the 1930's showed that the collection of summer heat for use during the winter was uneconomical.

Ernst Schönholzer, an engineer in Zwitzerland, looked at the problem in 1969, but on a larger scale, and without economic analysis. Below is a summary of his findings (HCW). His particular interest is in reducing city pollution during the winter, but it would also reduce fossil fuels consumption.



HEAT STORAGE
SECTION THROUGH SPHERE (HCW-380)

SINGLE DWELLING

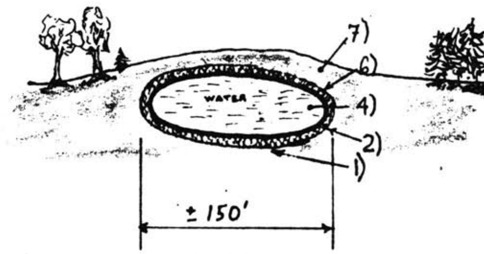
- Assume that a 195°F temperature can be attained in the storage: begin the solar heat collection on April 1 at an 85° storage temperature and continue until October 1, reaching 195°.
- Assume that the storage temperature drops back to [illegible]° at the end of the heating season (43[illegible]0 hours).
- Assume a seasonal heating demand of 40,000,000 Btu (MIT House IV used twice this amount, including domestic hot water).
- Use a cylindrical water container with a diameter equal to the height and equal to 20 feet (6000 ft^3 and about 48,000 gallons of water).

100 APARTMENTS

- Make the same assumptions as above:
  40,000,000 Btu/apartment/season, 4×10^9 Btu total for 100 apartments;
  the storage temperature is 85° April 1 and 195° October 1.
- Use a cylindrical water container with a diameter equal to the height and equal to 95 feet (600,000 ft^3 and about 4,500,000 gallons of water).

RESULTS

Schönholzer computed that if the heat were not used during the heating season, the temperature of the small tank would drop to 170° and that of the large tank would drop to only 135° (for the period October 1 to April 1). He made no economic analysis but suggested that the large installation would more likely be economical.



HEAT STORAGE
SECTION THROUGH DISC

A STORAGE CONTAINER

1) Excavate a disc- or hemisphere-shape in the earth;
2) Spray 3 feet of foam insulation inside of the excavation;
3) Pour or spray a thin concrete shell on top of the insulation, if necessary, or just
4) Water-fill a plastic bag of appropriate size on top of the insulation;
5) Pour or spray a thin concrete shell over the inflated bag, if necessary, or just
6) Spray 3 feet of foam insulation on top of the plastic bag;
7) Cover the insulation with earth (or other) if necessary.

COLLECTING HEAT

- The collectors might have to be more expensive, possibly of the focusing type, to attain temperatures of 195°. However, each square foot of collector will be saving larger amounts of fuel than if it were operated only in the winter.
- The collectors could operate year-round, not just in the summer, to furnish heat to the storage tank even as it was being used to heat. This might result in the use of a smaller tank than Schönholzer suggested, or instead, domestic hot water could be added as part of the heat load.
- MIT House IV collected 350 Btu/ft^2/day during the winter. It is not unreasonable to assume that this figure could double during the summer collection. If heat were to be collected only in summers, collection might average 126,000 Btu/ft^2/summer. To collect 40,000,000 Btu (an apartment's heating load), the collector would have to be about 400 ft^2, far less than normally required. Collectors might be able to be horizontal on flat roofs, instead of tilted.

There are many factors involved in the decision of whether or not to use solar energy for heating and cooling. Not only is there the moral issue of trying to use less fossil fuels and to pollute less in the heating/cooling process but there is also the economic issue of obtaining a reasonable return on the investment of a dollar. There are countless ways of evaluating 'reasonable return' and it is almost impossible to here suggest that even a typical example would provide a justified exploration into its definition. However, there are several factors which every accounting system will evaluate and which have been mentioned before:

- installation cost of the solar system
- maintenance cost of the solar system
- operating cost of the solar system
- savings in house cost and furnace cost
- savings in maintenance of furnace
- savings in fuel costs
- other costs and savings, for example, increased insurance costs, savings from government incentives on non-polluting devices

This thesis shows ways of decreasing the heat loss of buildings, of more advantageously using the gifts of nature to attain thermal comfort. In making the economic evaluation of whether or not to collect and use solar energy, the effort is usually made to balance increased costs against increased savings, primarily fuel savings. The determination of installation, maintenance, and operating costs of solar systems is still difficult, varying so greatly with design, location, and the people involved. But in trying to evaluate fuel sa-

(RUS-104)

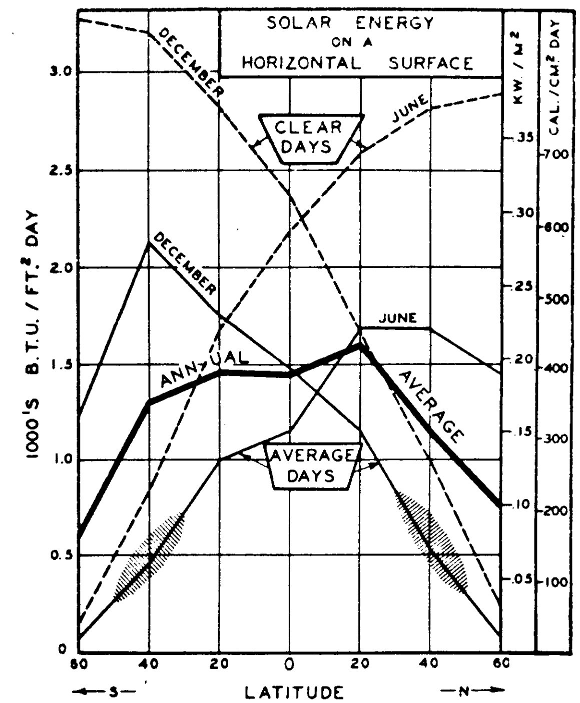


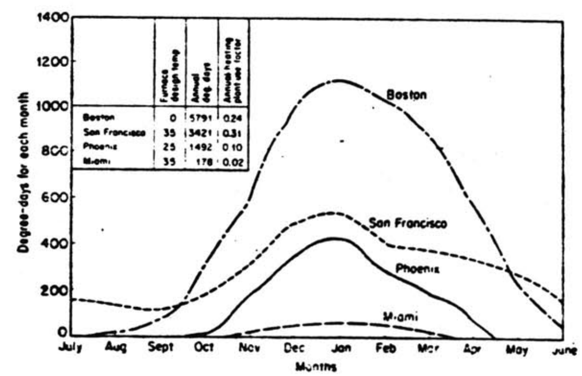
Fig. 1. Solar incidence on horizontal surfaces, average effect of latitude and season.

vings, it most simply can be said that if we know how many Btu's are required by the shelter and how many can be delivered to the shelter by the solar system, then, by knowing the cost of delivering this heat in a conventional way by oil, gas, or electricity, we can determine the fuel savings.

Each building differs in its heating needs, both in the way it is built and in the way it is used (the same building used differently will probably have different heating needs). The price of fuel varies greatly throughout the country and throughout the world. This section deals with the issue of climatic variations which affect how much heat the solar system can collect. The more Btu's that can be collected and delivered per square foot of collector surface, the greater will be the fuel savings per square foot of surface (and the higher can be the per-square-foot cost of the solar collection system).

Most basically, Tybout and Löf (SHE) and others have shown that cold weather with a lot of sunshine offers the best combination for economic success. (There are other considerations too such as the amount of wind and the radiational and reflective qualities of the immediate environment). Of course, as pointed out in INTRODUCTION TO THE UTILIZATION OF SOLAR ENERGY, a "moderate, fairly uniform, heating requirement throughout the year" (with a fairly uniform day-to-day, as opposed to month-to-month, distribution of demand with a fairly uniform distribution of sunny days) is the ideal means of utilizing the solar system to its fullest, but there are no such climates. Figure 1 shows that San Francisco has the most uniform temperature distribution of the four cities shown. Its cloudy and foggy days may make the use

'Fuel savings' ought to include more than just the monetary savings. In addition it should include some indication of intangible savings such as lessening pollution, conservation of fossil fuels, conservation of all the energy and resources needed to bring the fuel from the well to the shelter.



1 Fig. 10.6. Annual temperature variations for four United States cities. (From U.S. Weather Bureau data.) (IUSE - 225)

of solar energy disadvantageous, however. Figure 2 shows that a collector which can provide heat for 200 DD's (degree-days) per month is much too large for Miami, provides most of the heat needed in Phoenix, and is utilized the greatest number of days by San Francisco and Boston. A collector providing heat for 800 DD's would never be fully utilized except by Boston, and except for the three coldest months, it would not be fully utilized there either.

A quick look at Figure 1 is enough for us to realize that a collector large enough to provide for 100% of the heating demand will be utilized only for very short periods of time. Thus it is not enough to find the peak heating demand for the season and simply build a collector which is large enough to collect the necessary heat. We must find one which will use every square foot to the extent that each square foot pays for itself in fuel savings.

Dr Paul A Siple, at a Solar Energy Symposium at MIT in 1950, presented the map shown and described in Figure 3. It is shown here at the risk of its being used to make decisions about whether or not solar energy should be used for heating in certain parts of the country. Such has often been its use, unfortunately. Except where the sun never shines, it is engineeringly possible (though almost always economically very impractical) to build a big enough collector and a big enough storage unit to provide for all of a building's heating needs. Because of the low demand for heat in the South, where Dr Siple has shown maximum feasibility, the collectors would be needed very little, resulting in very small fuel savings and a very poor economic return on the large investment in a solar installation.

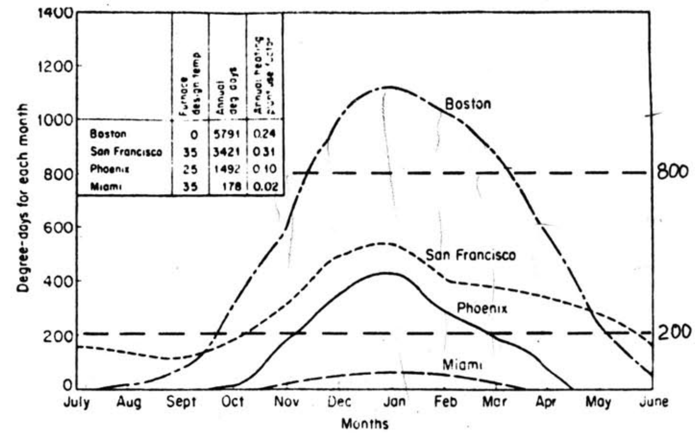
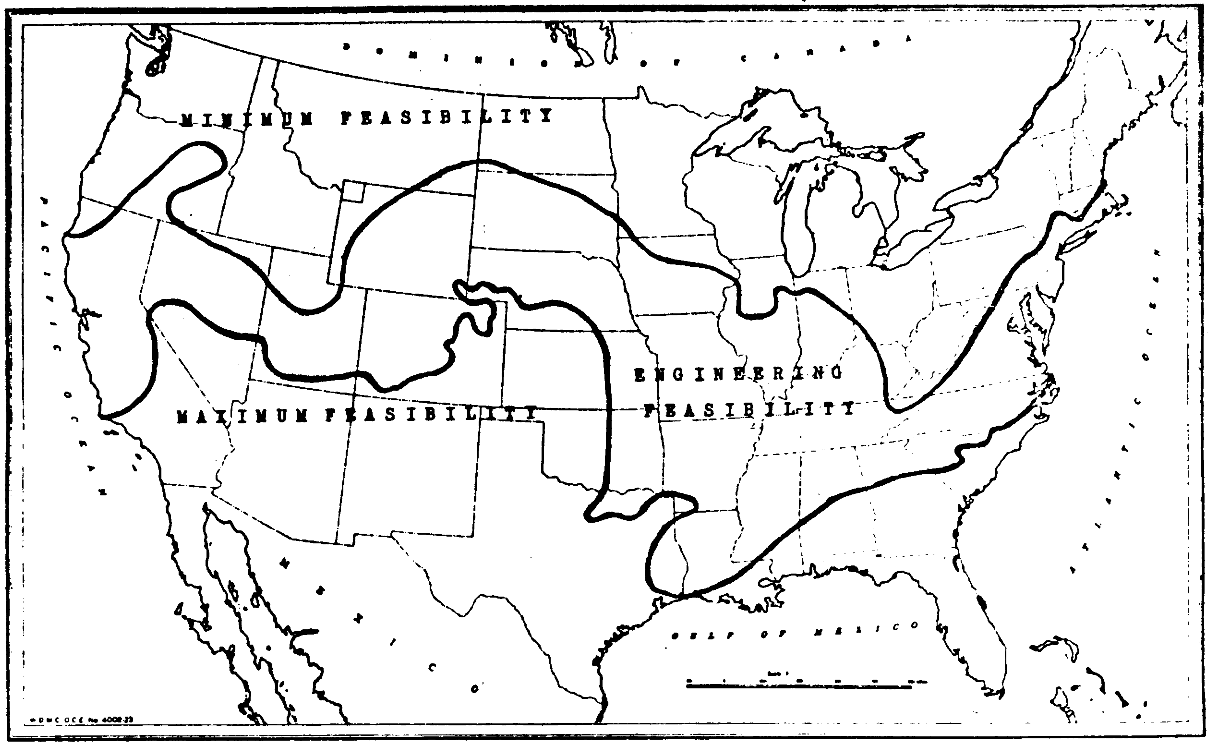


Fig. 10.6. Annual temperature variations for four United States cities. (*From U.S. Weather Bureau data.*) (IUSE-225)

2

If an auxiliary heating source "could handle the top 10% of the maximum anticipated requirement, it would save nearly 10% of the cost of the initial solar installation and still would only amount to less than 1% of the entire annual thermal requirement."
(IUSE - 224)



3

Feasibility of Solar Heating Systems (SHW)

Region of Maximum Feasibility, comprising Florida, the Gulf and southeastern coastal plains, Texas, New Mexico, Arizona, southern California and bordering areas. Here, heat requirements for evenings and the entire cool season can be supplied by solar radiation collection devices without elaborate or expensive engineering.

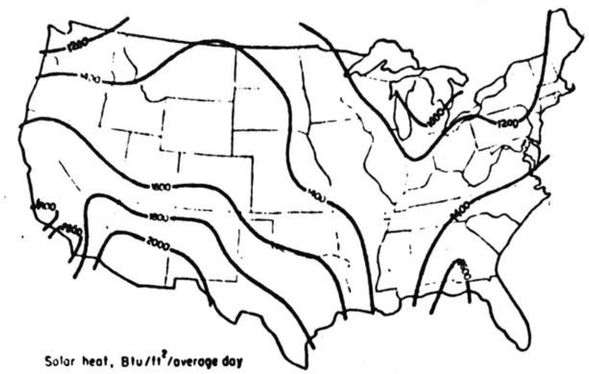
Region of Engineering Feasibility, comprising the central Atlantic coastal plains and piedmont, central Mississippi basin and plains, north central midwest and western states, and northern California. Here, solar radiation can supply most of the heating needs of Spring and Fall but will require special devices and careful engineering design to assure reliable and economical solar heating systems.

Region of Minimum Feasibility, comprising northern New England, New York, Pennsylvania, Virginia, Ohio, Michigan, Wisconsin, Minnesota, N. Dakota, Montana, Idaho, Washington and Oregon. Here, due to prolonged periods of intense cold, heavy cloud cover, and low angle of sun, solar rediation is entirely inadequate for winter space heating with present engineering methods. As supplementary heat source during late Spring and early Fall, and for lithosphere (sub-surface) rooms during summer, however, solar heating offers definite advantages in fuel economics and humidity control. In certain areas even the most elaborate solar heating systems will require thermal support from summer heat pump storage systems.

Figure 4 is a map of average daily insolation values in the US in Btu/sq ft/ average day. Like the map in Figure 3, it is very misleading, and cannot be used for work with solar energy heating. The figures given are for insolation on a horizontal surface (collectors are at a tilt, usually about an angle from the horizontal of latitude plus 5 to 25 degrees). Insolation on a horizontal surface varies greatly from one season to the next; trigonometry would make maps of average daily insolation for the winter months useful.

We can assume that a collector of 45% efficiency can be built within the continental United States; this has been done by most solar energy experimenters. After all of the climatic rhetoric regarding solar energy use has been digested and analyzed, the main criterion for collector performance is how many Btu's of sunshine strike each square foot of collector surface. Figure 5 is an illustration that Lawrence Anderson, former Dean of MIT's School of Architecture, used to show the quantity of sunlight which struck a given collector. When the sun is perpendicular to a collector at a tilt angle of β and at a northern latitude ϕ, it is at the same time perpendicular to a horizontal surface at a southern latitude of $(\beta - \phi)$. By finding that value of insolation, we find the approximate value of insolation on the collector. (altered of course by increased travel through the atmosphere and by local atmospheric conditions such as clouds and smog). The same value is that of summer insolation on the northern latitude $(\beta - \phi)$ on a horizontal plane.

Once the value of possible insolation can be found, it is necessary to find out how local conditions of cloudiness and air cleanli-

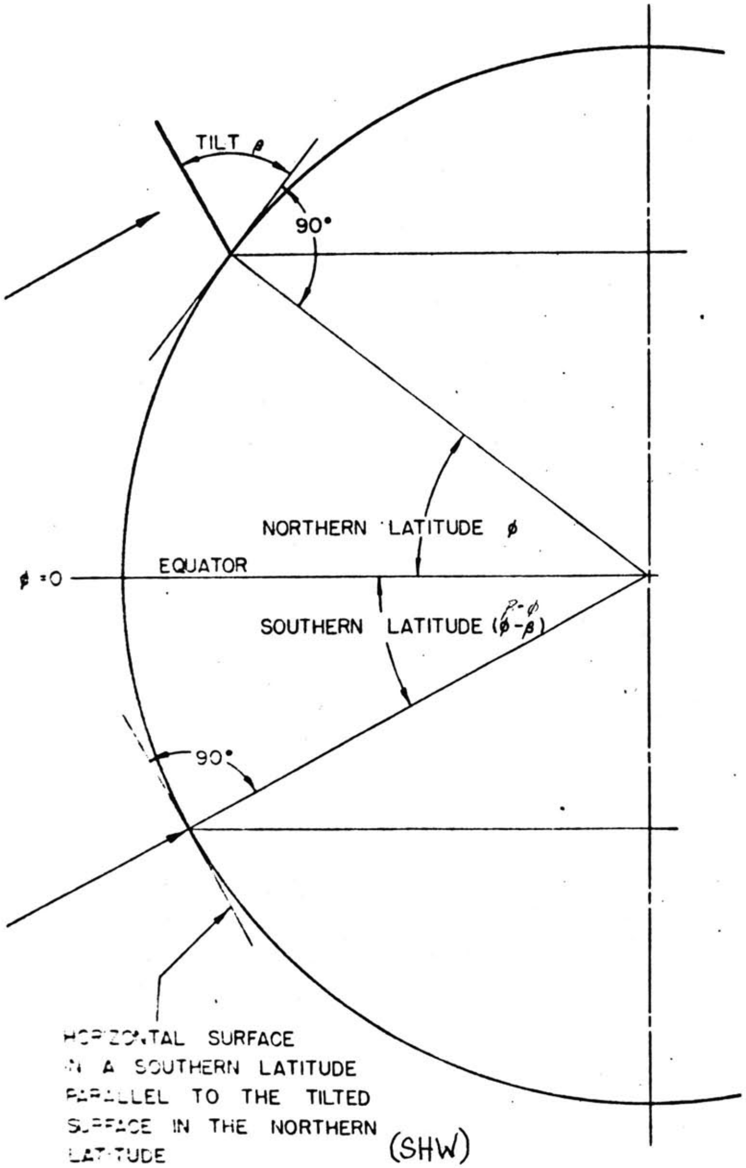


4 Fig. 3.1. Distribution of average daily insolation in the United States [from I. F. Hand (1953), courtesy *Heating and Ventilating*]. (USE - 31)

The local weather bureau may have this information.

These values can be found in "Monthly Maps of Mean Daily Insolation For the United States" by Iven Bennett in SOLAR ENERGY, July-Sept '65; or in ASHRAE HANDBOOK OF FUNDAMENTALS.

EFFECT OF TILT



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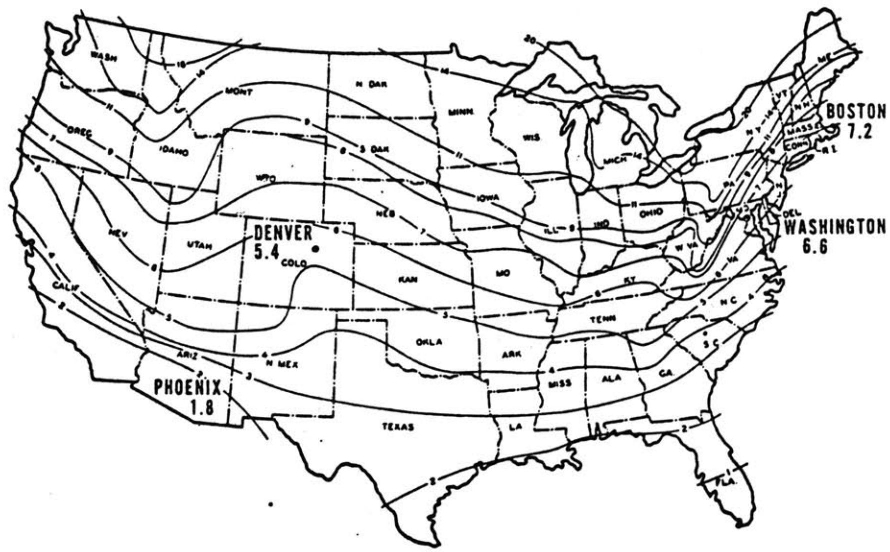

Degree days per sunshine hour based on December and January data. The larger the number, as shown on this map, the more elaborate is the heating system required. By Dr. Maria Telkes.

FROM HEATING AND VENTILATING'S REFERENCE SECTION

7

ness (atmospheric transmissivity) affect that which is collectible. The first designers, in order to determine the length of time for which it was necessary (and economical) to store heat to get through sunless days, had to go through agonizing information collecting and analyzing. Tybout and Löf (SHE) and others have shown the optimum to lie within a range of overnite (one day) to three days. (Thomason stores heat five days and longer but cost figures are not available. This may not be economically optimal in traditional economic terms but may be in his). It has thus been found that since an auxiliary heating system is necessary to get us through a long series of sunless days, it is the number of cloudy days (when we cannot collect heat) versus the number of sunny days (when we can collect heat) which is of importance in determining how much heat will be collected.

Figure 6 was prepared by F W Hutchinson and W P Chapman at Purdue in their effort to find the heating affect of the sun penetrating through glass facades of buildings. It shows, for representative cities, F, "the ratio of the average number of sunshine hours in the period from October 1 to May 1 to the maximum possible sunshine hours (at the latitude of the city) for the same period." (RBS)

Dr Maria Telkes has elaborated on this information in Figure 7. For the months of December and January, the map shows the number of degree days per sunshine hour. By finding the number of degree days for a particular locality from the weather bureau (utility companies also have this information) and dividing it by the corresponding number on the map in Figure 7, the number of sunshine hours for the month will be found. Then by finding the amount of sun which strikes

Of course, if we try to carry the total heating load with just solar energy, the number of successive cloudy days becomes important in the design of storage capacity, but such systems are not now economical.

Table 1—Values of Usage Ratio, F, for Representative Cities.

[F is ratio of the average number of sunshine hours in the period from October 1 to May 1 to the maximum possible sunshine hours (at the latitude of the city[a]) for the same period.]

City	F
Albany, N. Y.	0.463
Albuquerque, N. M.	0.770
Atlanta, Ga.	0.522
Baltimore, Md.	0.553
Birmingham, Ala.	0.510
Bismarck, N. D.	0.546
Boise, Ida.	0.540
Boston, Mass.	0.540
Burlington, Vt.	0.419
Chattanooga, Tenn.	0.503
Cheyenne, Wyo.	0.666
Cleveland, O.	0.408
Columbia, S. C.	0.511
Concord, N. H.	0.515
Dallas, Tex.	0.470
Davenport, Ia.	0.539
Denver, Colo.	0.705
Detroit, Mich.	0.429
Eugene, Ore.	0.439
Harrisburg, Pa.	0.495
Hartford, Conn.	0.532
Helena, Mont.	0.521
Huron, S. D.	0.579
Indianapolis, Ind.	0.507
Jacksonville, Fla.	0.400
Joliet, Ill.	0.530
Lincoln, Neb.	0.614
Little Rock, Ark.	0.513
Louisville, Ky.	0.514
Madison, Wis.	0.604
Minneapolis, Minn.	0.527
Newark, N. J.	0.550
New Orleans, La.	0.370
Phoenix, Arizona	0.590
Portland, Me.	0.525
Providence, R. I.	0.542
Raleigh, N. C.	0.570
Reno, Nev.	0.637
Richmond, Va.	0.594
St. Louis, Mo.	0.567
Salt Lake City, Utah	0.592
San Francisco, Cal.	0.615
Seattle, Wash.	0.340
Topeka, Kans.	0.612
Tulsa, Okla.	0.560
Vicksburg, Miss.	0.447
Wheeling, W. Va.	0.408
Wilmington, Del.	0.558

6

(RBS - 113)

the collector each sunny hour (as described above), a rough, but important approximation can be found for the total amount of direct sunlight which hits the collector.

In summary, we have:

$$\frac{\text{degree days/month}}{\text{the number on Telkes' map}} = \text{sunshine hours/month}$$

$$\text{sunshine hours/month} \times \text{insolation/sunshine hour/sq ft} = \text{insolation/month/sq ft}$$

When we use this method with the information on pages 5, 6, and 7 in the article about MIT House IV, 'Progress in Space Heating with Solar Energy' (reprinted in the appendices), we find that it gives us smaller values than what they recorded. Figure 8 reproduces Figure 6 from that article. It shows that considerable amounts of solar energy was striking the collector when the temperature of the collector was not high enough to justify collection of that energy (most of this energy is diffuse radiation through clouds which the above method does not try to include). The values which we find by using the above method more nearly represent the curve shown as 'solar incidence when solar collector operating'.

It has been the intention here to suggest a means of circumventing the very valuable and expert work done by engineers in this field in an effort to give laymen a point from which to begin their explorations. Engineering work of such notables as H C Hottel, B B Woertz, A Whillier, and others may be necessary for detailed predictions of collector performance, however. Continued work on such a simplified analysis will result in progressively better approximations which might readily be made by laymen.

Continued refinement of this method could lead to simple estimating graphs.

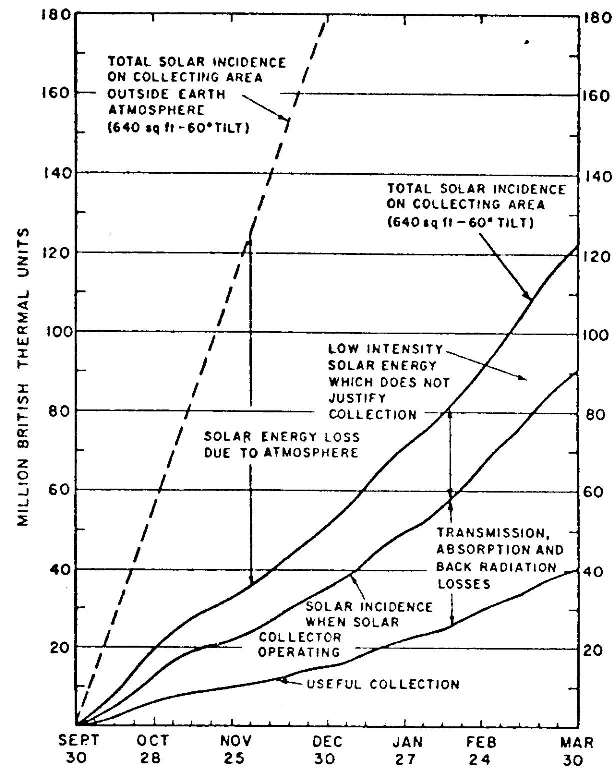

Fig. 6 Solar collector performance during the winter season 1959-1960. Cumulative values for every week are plotted in million Btu

8 (PIS-5)

See especially "The Performance of Flat-Plate Solar-Heat Collectors", Hottel & Woertz. (PFP)

The past twenty or thirty years has seen a wide range in the extent to which different applications of the utilization of solar energy have been implemented. Developing the engineering feasibility has not been enough of an impetus to accomplish wide-spread use of this free source of energy. G O G Lof, D J Close, and J A Duffie, all three of whom have been extensively involved in the use of solar energy, offer the following "Systematic Approach to Solar Energy Development - The Blueprint" (Reprinted from PFS - 247-9)

A SYSTEMATIC APPROACH TO SOLAR ENERGY DEVELOPMENT

THE BLUEPRINT

We believe that the following (idealized) procedure will be advantageous where the object of the project is ultimately the provision of a useful system or process to meet an energy need. These steps are not all sequential: they can be taken in parallel (in part) and with "feedback" from one to another. (It is also recognized that in many cases studies will be carried out for scientific curiosity and need no final usefulness as justification.)

First step – determination of needs

This step, which is one of the most important of the whole study, determines the need which the final developed process is to fill. The term need is used in its broadest sense and covers the social, political and economic requirements which the process must satisfy if it is finally to be a marketable concept.

The following questions are typical of those which must be answered in studies leading to a reliable appraisal of needs. The list is not intended to be complete, other questions requiring answers in particular circumstances.

(i) Should the facility be individual family size, or community size with distribution of heat, power, water, ice or other product?
(ii) Must its operation be automatic, or will the user be prepared to take some part in its control?
(iii) Might the facility cause changes in the life patterns of all or part of the community, so that either it is initially accepted and then rejected? Does it produce desirable or undesirable side effects such as secondary industry, or unemployment?
(iv) What are the meteorological conditions?
(v) If comparable service is being provided by an existing facility employing a conventional energy source, what advantages (and disadvantages) will there be by virtue of substituting the solar energy supply? What are the alternatives to solar energy, in the location in question?
(vi) What are the possibilities of interest by manufacturers (i.e., what is the profit potential) in undertaking production and sale of solar equipment?
(vii) What proportion of their income will a community or an individual pay for such a facility?
(viii) What are the possibilities of subsidies from government and other sources during early stages of commercialization?
(ix) If import of knowhow, materials or finished products is required, because of local unavailability, what tariff and quota restrictions may have to be faced?

The answers to questions of this sort will show, firstly, whether the project has any prospect of success in the foreseeable future and, secondly, the ultimate goals to be fulfilled in engineering the process.

Second step – broad choice of the process

To any engineering problem, there are usually several solutions. The task set in this step is to sift the possible solutions and determine, on the basis of existing information, the most promising from the standpoint of technical workability. (Economics are usually associated with technical factors, but economic analysis is listed here as a separate step.) Taking the example of solar refrigeration, the choice of possible solar processes ranges from vapor compressors driven by a solar electric generator, to intermittent absorption cycles. There will also be alternatives operated from other energy resources.

Third step – preliminary economic analysis

Through use of available and cost data on materials, fabrication methods, transport, installation, profits and other pertinent information, initial investment costs and operating expenses are estimated for the feasible processes identified in Step 2. These are compared with the requirements established in Step 1, and a decision to continue or abandon the development is made. Through each of the following steps, the cost study is refined as more information becomes available, further decisions being based on the revised figures.

Fourth step – establishment of a theoretical basis

Generally, a certain amount of scientific and engineering knowledge, either not in existence or not yet applied to the particular process, will be required. The possession of this knowledge enables mathematical models of the process to be made, and the studies performed with the models greatly simplify the prototype design. The availability of computers has shortened and simplified this step, owing to the enormous amount of information which can be processed in a very short time.

Fifth step – prototype design and testing

The purpose of the prototype is twofold. Firstly, it checks the validity of the theoretical studies and, secondly, it provides a vehicle for further development, the final result of which is the "finished" product. Thus the prototype establishes the context in which further work is done. This means that it must be designed with the final economic and social requirements in mind.

Sixth step – development

This involves the transformation of the prototype design into a marketable item, and may involve procedures as different as, on the one hand, the complete redesign of a heat exchanger and, on the other, the enclosing of working parts in an attractive and functional housing. This step forces the prototype into a form which satisfied the requirements as found in Step 1.

Field testing is part of this step, and evaluates the effects of imponderables (such as dust buildup on glass or plastics, damage caused by animals, etc). The objective of field testing is to put the developer into the position of being able to *guarantee system performance over an extended period of time*.

Seventh step – marketing

This step is the "acid test" of the whole project. If the needs were correctly established by Step 1, and if the development in Step 6 adequately fulfilled these needs, then the marketing should be successful. If the real needs have not been met, it may not be successful.

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HOW TO BE YOUR OWN ELECTRICIAN George Daniels, 144 pp., $3.95. "All you need to know to do your own wiring"

HOW TO BUILD YOUR HOME IN THE WOODS Bradford Angier, 310 pp., $7.00, $2.45 ppbk. "A pretty fair guide to building the traditional north woods log cabin and other structures. Good discussions of hot and cold storage, fireplaces, oil drum heaters and the rest of cabin life. More nitty-gritty basics than the new editions of Kutstrum's book (The Wilderness Cabin)"

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"Your Own Water-Power Plant" THE MOTHER EARTH NEWS, #13 & #14, reprint of 1947 POPULAR SCIENCE series of 5 articles; includes information on dams.

Periodicals

Clear Creek One South Park, San Francisco 94107, monthly, $7.50/yr $13.00/2 yrs.

The Green Revolution The Green Revolution, Route One, Box 129, Freeland, Md 21053, monthly, $4.00 yr.

Lifestyle P.O.Box 1, Unionville, Ohio 44188, bimonthly, on alternate months with THE MOTHER EARTH NEWS.

The Mother Earth News 1899 Hubbard Road, North Madison, Ohio 44057, bimonthly.

Organic Gardening and Farming 33 E. Miror St., Rodale Press, Emmaus Pa 18049, monthly, $5.85/yr.

Plants and Gardens Brooklyn Botanic Garden, Brooklyn, NY 11225, quarterly, $3.00/yr.

Wood Heat Quarterly Lowther Press, R.D.1, Wolcott, Vt 05680, 4 issues yr., $3.00/yr.

Wood Preserving Formerly WOOD PRESERVING NEWS.

LOCAL AND NATIONAL GROUPS, ORGANIZATIONS, AND INSTITUTIONS
having or trying to have a positive effect on the environment

American Forestry Association
919 17th St NW
Wash DC 20006
"Promotes conservation of forests and allied resources"

American Institute of Architects (AIA)
1785 Mass Av NW
Wash DC 20036, ph 202 265 3113
Michael B Barker, Administrator
Department of Environment and Design

American Wood Preservers Institute
1651 Old Meadow Rd
McLean Va 22101
ph 703 893 4005

Baker Manufacturing Co
Evansville Wis 53536
free info on hand pump stands

Boston Environment Inc
14 Beacon St Boston 02108
ph 227 2669
"Environmental information center attempting to provide information and referrals to Boston residents" - have information and library

Bucknell Engineering Co
10717 E Rush St
South El Monte Ca
sell wind generators

Cambridge University, Alexander Pike, University Lecturer in Architecture
Technical Research Division
Dept of Arch, 1 Scroope Terrace
Cambridge CB2 1PX England

Center for Environmental Structure
2531 Etna St Berkeley Ca 94704

Deeprock Mfg Co
Box 870 Opelika, Alabama 36801
sells Hydra-drill for $350, to dig your own well

Dempster Industries Inc
P O Box 848
Beatrice Nebraska 68310
sell good equipment for pumping water

Dyna Technology Inc
P O Box 3263
Sioux City Iowa
sell wind generators

Earth Move
P O Box 13036
Washington DC 20009
information on how to convert existing septic tanks to the collection of methane; sell a kit ti convert cars to methane

Ecology Action
P O Box 9334
Berkeley Ca 94709

Environmental Action Inc
2000 P St NW
Washington DC 20036

Environmental Protection Agency
Washington DC 20460

Federal Extension Service
US Dept of Agriculture
Wash DC
"Education programs and field agents help development of resources, conservation practices and recreational use."

Forest Service
US Dept of Agriculture
Wash DC
"Manages national forests and grasslands, offers technical and financial aid and research to landowners for forest and wildlife management"

Friends of the Earth
30 E 42nd St
NYC 10017
"Aggressive international conservation organization"

Goldblatt Tool Co
511 Osage
Kansas City Kansas 66110
amazing catalog of specialized builder's tools
free

Harmony
872 Mass Av
Cambridge, Mass 02139
ph 354-1248
"self-supporting ecology group will help anybody interested in solving environmental problems"

Heller-Allen Co
Corner Perry & Oakwood
Napoleon, Ohio 43545
sells equipment for pumping water

Hilfiker Inc
3900 Broadway
P O Drawer L
Eureka Ca 95501
sells sewage utility equipment

John Muir Institute for Environmental Studies
451 Pacific Av
San Francisco Calif 94133

James Leffel & Co
Springfield Ohio 45501
sells good but expensive hydraulic turbines

Metropolitan Ecology Workshop
74 Joy St
Boston 02114
ph 723-6894
"Working on ecology projects at the community level in Boston. Have home ecology program...."

National Academy of Science
has information on resource reserves

National Center for Urban and Industrial Health
US Dept of Commerce
Washington DC
Office of Solid waste: "Research in waste disposal methods and controls"
Environmental Sanitation Program: "Technical assistance and standards development for recreational areas, housing hygiene, urban noise and crowding. Conducts and supports research and training"

National Forest Products Association
1619 Mass Av
Washington DC 20036

Plastics Pipe Institute
250 Park Ave
NYC 10017

Quirk's Victory Light Co
33 Fairweather St
Bellevue Hill
NSW 2023
Australia
sells wind generators

Rachel Carson Trust for the Living Environment, Inc
8940 Jones Mill Rd
Wash DC 20015
"Serves as clearinghouse of information on environmental contamination and ecology in general"

Rife Hydraulic Engine Manufacturing Co
Box 367
Millburn NJ 07041
sells hydraulic rams

Sierra Club
Huron Ave
Cambridge, Mass
Paul SwateK, Regional Manager
ph 862-9330
National Office:
1050 Mills Tower
San Francisco 94104

Small Homes Council - Building Research Council
U of Illinois
Urbana Illinois
has publications on building techniques

Soil Conservation Service
US Dept of Agriculture
Wash DC
"Works with local water and soil conservation districts to provide technical assistance in planning and implementing local projects. Conducts soil surveys, publishes basic water conservation and land-use data"

Southern Forest Products Association
P O Box 52468
New Orleans Louisiana 70150

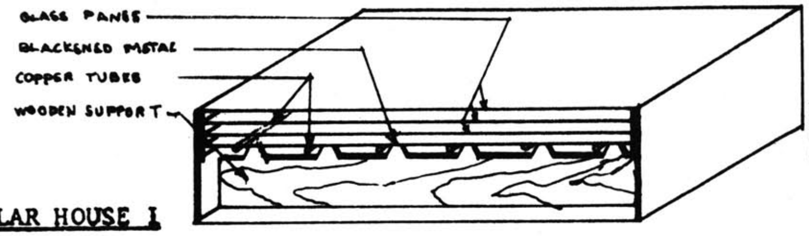
Stanford Research Institute,
Stanford University,
assembles information of solar-related activities; has reference library, solar engineering exhibit.

Sunwater Co
10404 San Diego Mission Rd
San Diego Ca 92129
sells solar stills

USDA Forest Products Laboratory
Madison Wis 53705
Published Research Note FPL - 0134, "Experimental Chromate Finish" a spray-on, 51¢/gal four-year wood preservative.

World Wildlife Fund
910 17th St NW
Washington DC 20006
Published "What You Can Do" by Malcolm Wells
10¢, 8pp.

Zomeworks
P O Box 712
Albequerque, N M 87103



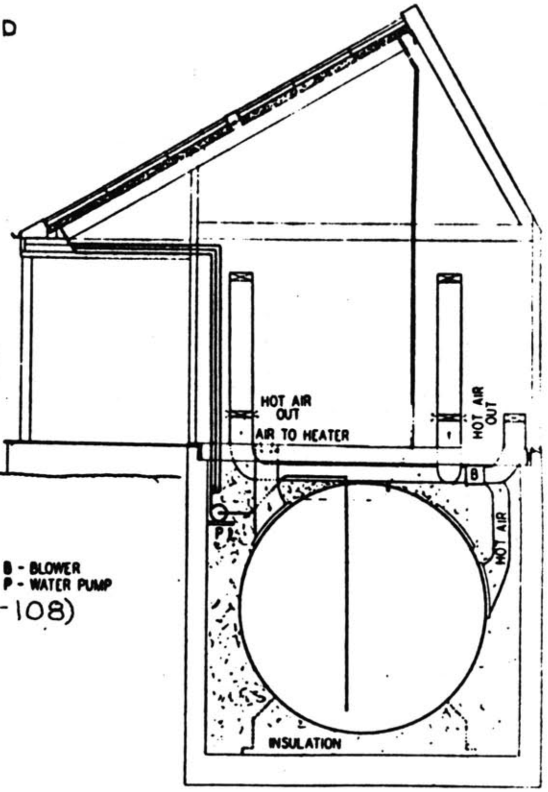
SECTION OF A TESTED SOLAR-HEAT COLLECTOR

2
(PFP-92)

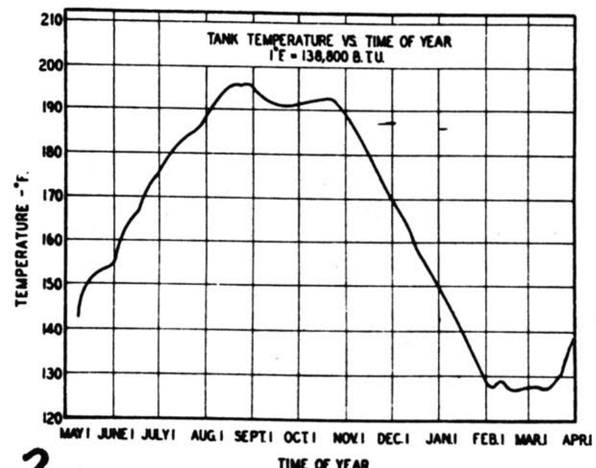
MIT SOLAR HOUSE I

Modern research into the utilization of solar energy began in the late 1930's at the Russian Heliotechnik Institute in Tashkent and with funds from Dr. Godfrey L. Cabot, MIT '81, at Harvard and MIT. The first solar-heated house was built at MIT in 1939 (figure 1). Its main purpose was to develop the methods for the calculation of the performance of the solar energy collectors. The two-room laboratory building had mounted on its south-facing roof a 360 sq ft blackened copper sheet collector behind three air-spaced glass plates in insulated boxes (figure 2). Water from the 17,000-gal basement tank (about 2000 cubic feet) was circulated through copper tubes soldered to the copper sheet. In addition to the collection of heat during the winter, heat was also captured during the summer and stored in the large tank for winter use. No auxiliary heat was needed for two seasons, since the minimum temperature reached by the collecor was 125° F, as seen in Figure 3. Economic analysis, however, showed that long-term heat storage was not practical. Equations were derived by H. C. Hottel and B. B. Woertz for the performance of the collectors with varying numbers of glass plates as a function of the outdoor and the collector temperature. Their publication, 'The Performance of Flat-Plate Solar-Heat Collectors' is still the basic guide for flat-plate collector design.

Fig. 5. The first solar house, Cambridge, Mass., 1939.



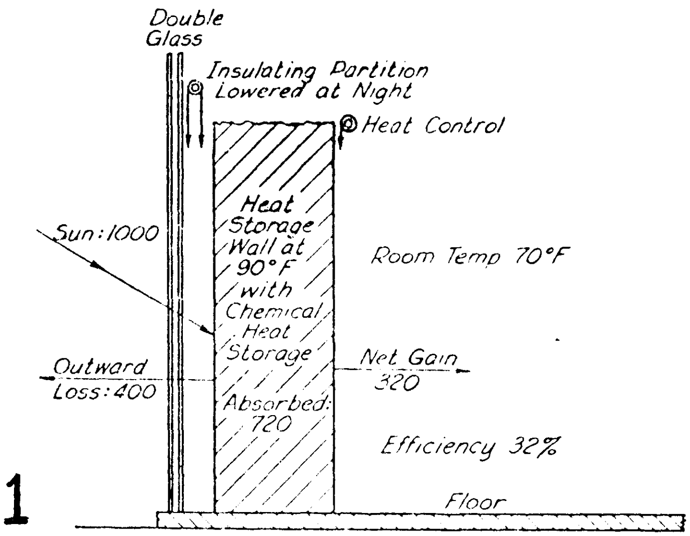
1
B - BLOWER
P - WATER PUMP
(RUO-108)



3
Fig. 6. Tank temperature in the first solar house.
(RUO-108)

It is believed that higher efficiency of operation can be achieved by placing the heat storage units near the collector and within the confines of the space which is to be heated. The maximum limit of such proximities can be achieved by letting the collector and storage unit be one and the same, and by using this collector-storage unit as one wall of the living space (see figure 1). Such was the design of MIT's solar house II. Figures 2 and 3 show the 8-foot-high, 14 x 44 ft building divided into seven 4-foot-wide cubicles for the purpose of testing seven variations of collection-storage-heating.

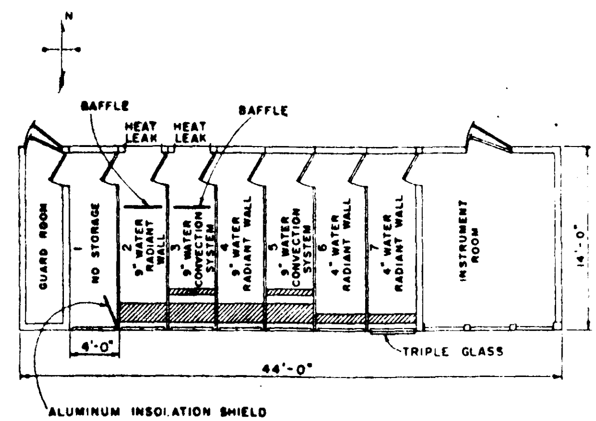
A G H Dietz and Edmund L Czapek in their article 'Solar Heating of Houses by Vertical Wall Storage Panels' in Heating, Piping and Air Conditioning, (~1947), detail the procedures, the problems, and some conclusions. In summary, six of the cubicles had double glass on the south front, the seventh having triple glass. The sun's rays would penetrate through the glass to the storage units immediately adjacent to the glass. The storage units would, as a result, heat up. In some of the cubicles this heat would be radiated by the storage units to the room. In other cubicles the heat would be transferred by convection (figures 4 and 5). Each cubicle had a set of double shades which were automatically lowered at night or on sunless days to conserve the stored heat. The storage medium was either water, which stored sensible heat, or salt which utilized heat of fusion, changing from solid to liquid at 90F and storing 100 Btu per pound. Temperature



1

Fig. 5. Sun wall chemical heat storage.

Figures are in Btu per sq ft per day. Dec.-Jan. average conditions for the vicinity of Boston. (SHH-72)

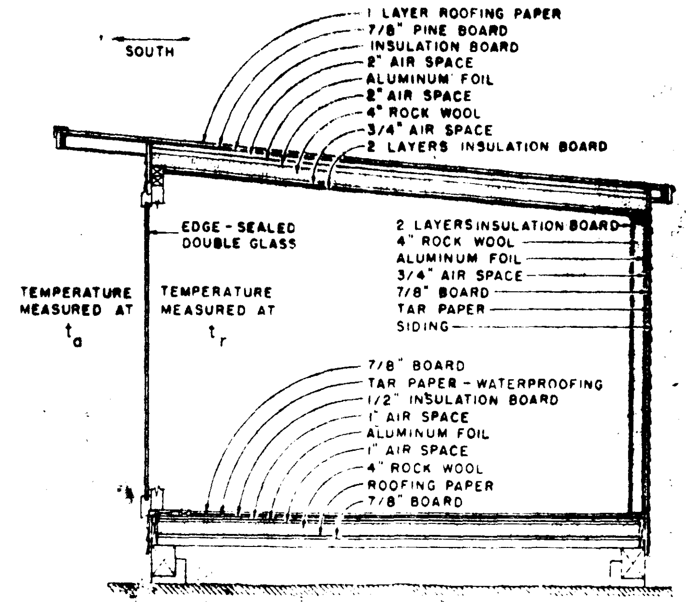


2

Fig. 2—Plan of test house showing arrangement of test cells

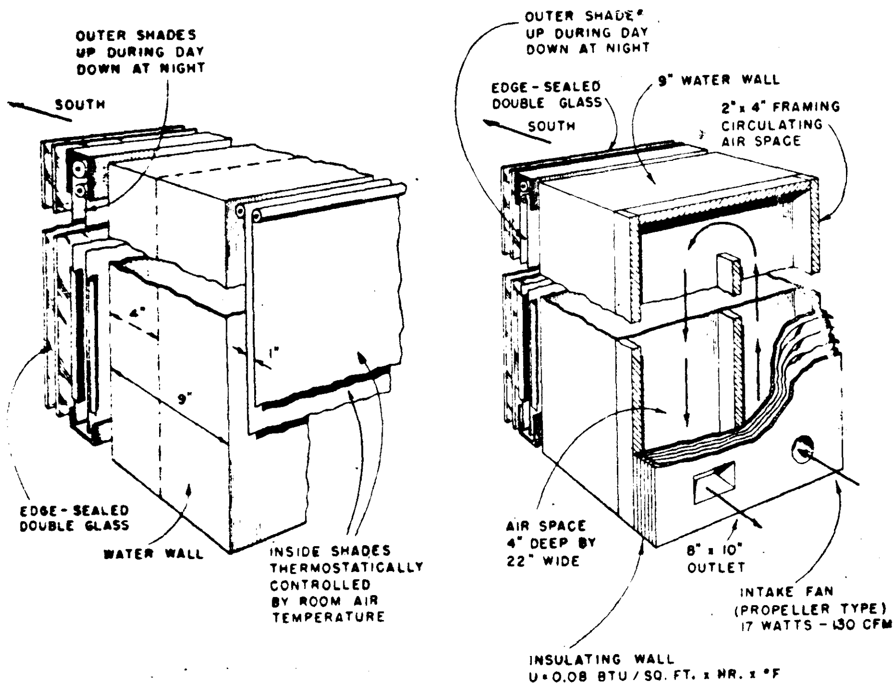
(SHVW-2)

stratification within the storage media, heat loss of the system through the glass to the outside, and the complications of trying to increase the efficiency led to the conclusion that further research in this direction would not bring satisfactory solutions to the solar heating problem.



3 Fig. 3—Cross section of test house showing construction

(SHVW-2)



4 Fig. 4—Schematic representation of solar energy collecting units 5

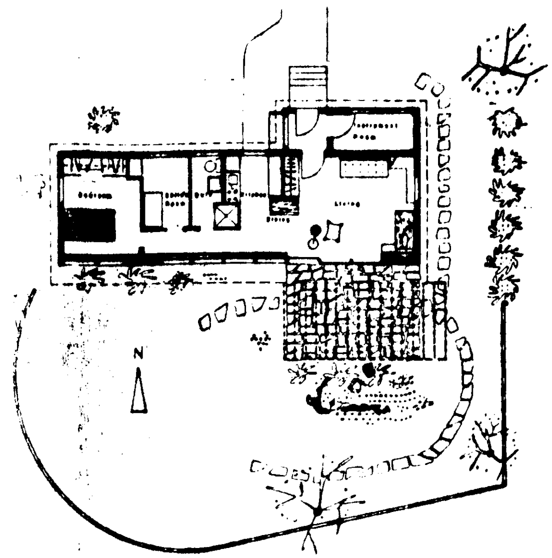
(SHVW-2)

MIT SOLAR HOUSE III

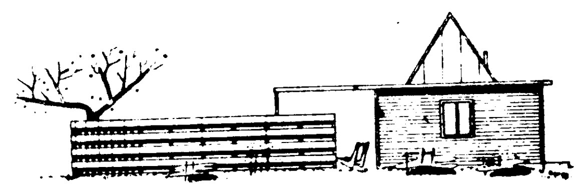
In 1948 MIT remodelled house II, converting it into a small home of 608 sq ft for a married student and his family. (Figure 1,2,3) A collector tilt of 57° south was used (latitude plus 15°) to optimize the collection of winter sun. In order to require auxiliary heating (this concept is discussed elsewhere in the paper), the collector (400 sq ft) and the water-storage tank (1200 gallons, about 150 cubic ft) were purposely underdesigned. The performance of the system was in close agreement with the predictions based on past experimentation, and supplied about three-quarters of the heating load. Solar energy was also 'collected' through the large south-facing windows (shaded by an overhang in the summer), often necessitating ventilation of excess heat during sunny winter weather.

Figure 4 shows the details of the collector. Copper tubes, 3/8 in. in diameter, 8½ ft long and spaced 6 in. on center, were soldered to the bottom of the collector. The surface of the air space below the tubes was faced with aluminum foil, behind which was 4 in of mineral wool insulation to reduce the heat loss from the collector to the interior of the house (such a loss reduces the temperature, and thus the efficiency of the collector). The tubes were connected to 3/4 in copper tube headers at top and bottom.

South-facing glass totaled 180 sq ft, of which 26 sq ft was double pane and 154 was triple. (Section two of this thesis shows the energy-economic tradeoffs between these two options).



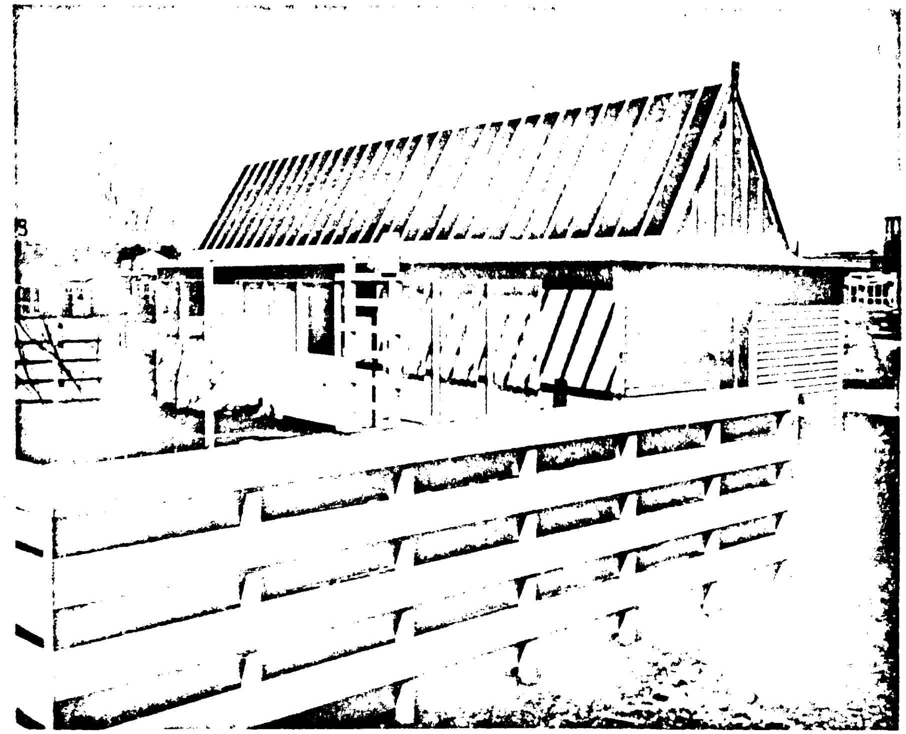
1 FIG. 5—Plan view of experimental solar energy house built at M. I. T. Note large glass areas on south wall.

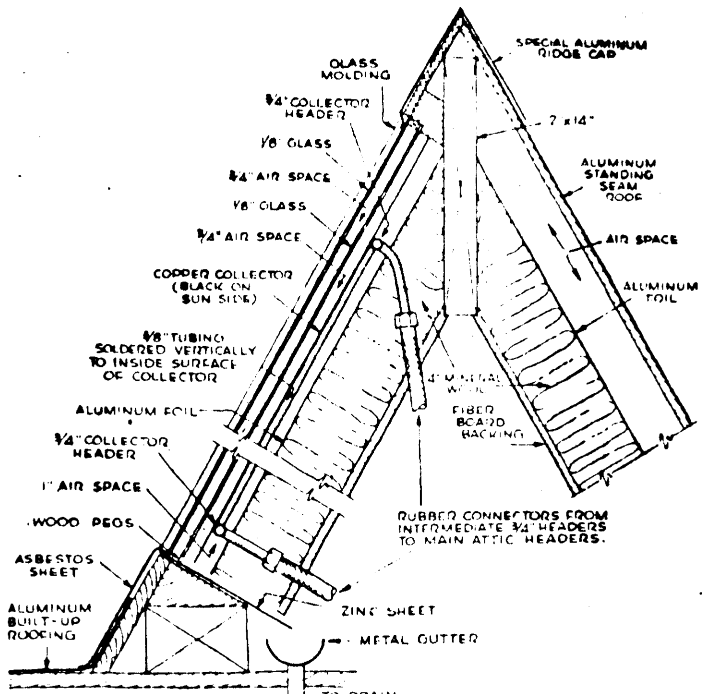


2 FIG. 6—East elevation of M. I. T. solar house. Solar energy collector was located on roof gable, which also housed energy storage tank.

(HSPR-47)

3 (RUS-109)





COLLECTOR DETAIL

4 (HSPR-48)

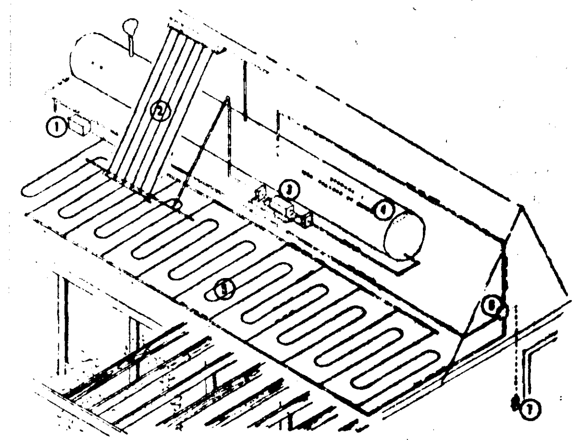
FIG. 7—Details of solar energy collector used on experimental house. Water was used as energy collecting medium, and unit was designed so as to drain when not in use. This eliminated need for anti-freeze solution during winter.

Figure 5 schematically shows the collection system, the two energy transport systems, the storage tank, and the radiant heating panels. The storage tank was 36 in. in diameter and 30 ft long and was placed in the attic space; such were the constraints of the remodelling problems. It is much better to have minimal surface area per cubic foot of storage, and because of the weight of water, ground level location is preferred. It is also desirable to locate the tank so that the lost heat is absorbed by the living quarters. Its capacity of 1200 gal provided 25 pounds of water per sq ft of collector and made it possible to carry the heating load for two consecutive sunless days (assuming that the storage water was at its maximum temperature at the start of those two days). Three auxiliary immersion heaters of 4 kw capacity each, were installed in the storage tank near its outlet.

A dry collector on the roof started the collector pump when its temperature reached 5° above the storage temperature; circulation continued as long as this condition existed. Such a method prevents operation during momentary periods of sunshine and the delivery of warm storage water to a cold collector. When the pumps stopped, the water drained back into the storage tank and thus did not require anti-freeze.

The radiant heating panels operated in a conventional way. When the thermostat called for heat, the pump began circulation and the mixing valve mixed warm water from the storage tank with return water from the panel, as required by the demand.

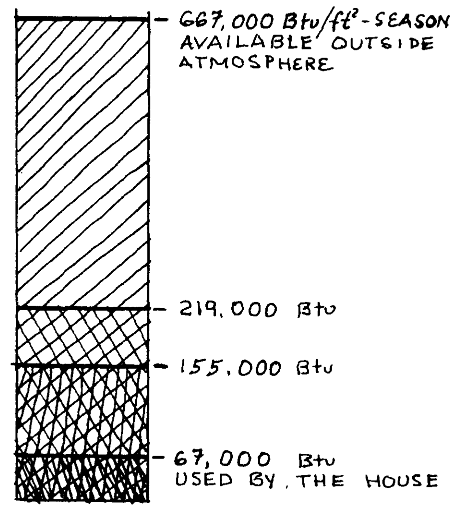
Before discussing the data it is interesting to note the following figures (graphically shown in figure 6):



5
(HSPR)

FIG. 8—Schematic of solar heating system. 1. Radiant panel pump. 2. One of 15 solar energy collectors. 3. Flow diverting valves and collection pump. 4. Solar storage tank: 1200-gal. water capacity. 5. Radiant panel. 6. Mixing valve. 7. Room-temperature control. In original house, radiant ceiling panels were used to transmit heat to occupied spaces. New test house will use conventional warm-air heating system.

6



- 667,000 Btu of solar energy in one heating season would strike one square foot of surface facing south and inclined 57° OUTSIDE THE EARTH'S ATMOSPHERE.

- 219,000 Btu would strike this same surface at sea level.

- 67,000 Btu per square foot was actually available and used for house heating during the season.

The huge drop from 667,000 Btu theoretically available to 67,000 Btu actually used is largely the result of the characteristics of the atmosphere and is unavoidable. However, 30 percent of the energy which struck the collector was actually used for heat, a respectable amount and a figure which is hard to improve upon.

Figure 7 shows the performance data for three heating seasons. To find heating load, the sum of all of the energy delivered to the building from appliances and animal sources is subtracted from the building heat loss (in conventional systems such contributions are usually ignored). Note that the percentage of heating load carried by solar energy includes both that energy which was collected by the collection system and that which entered the house through the windows. Changes in the piping system were responsible in large part for the improved performance during the 1951-52 season. The changes improved and equalized the collector circulation of water over the surface of the collector.

Prof A L Hesselschwerdt, Jr, a member of the MIT solar research team, wrote the article, "Heating by Sunpower: A Progress Report", from which a lot of the previous material was taken. He concludes as follows: (HSPR)

The house in question was located in a location where climatic

1949-50

	Oct.	Nov.	Dec.	Jan	Feb	Mar.	Apr.
Building Heat loss - BTU x 10^-3	5332	6300	7440	7099	8596	8959	5490
Heating Load ~ BTU x 10^-3	4030	4778	6231	5766	7280	7895	4350
Percentage of Heating load a) Solar Energy	100.0	[illegible]	83.1	55.1	50.0	84.7	91.8
b) Auxiliary Heating	0	14.0	[illegible]	44.9	50.0	15.3	8.2

1950-51

	Oct.	Nov.	Dec.	Jan	Feb	Mar.	Apr.
Building Heat Loss ~ BTU x 10^-3	4032	5414	7782	7961	8030	6882	4464
Heating Load ~ BTU x 10^-3	2621	3818	6344	6547	6792	5592	3270
Percentage of Heating Load a) Solar Energy	100.0	88.8	75.4	68.6	60.5	62.4	98.8
b) Auxiliary Heating	0	11.2	24.6	31.4	39.5	37.6	1.2

1951-52

	Oct.	Nov.	Dec.	Jan	Feb	Mar.	Apr.
Building Heat Loss ~ BTU x 10^-3	3332	5815	8002	8400	7891	7247	4345
Heating Load ~ BTU x 10^-3	2010	4479	7004	7139	6568	5845	2947
Percentage of Heating Load a) Solar Energy	100.0	100.0	78.0	62.6	86.8	76.7	100.0
b) Auxiliary Heating	0	0	22.0	37.4	13.2	23.3	0

7 (HSPR) FIG. 9—Summary of heating data collected during three years of testing. Note high percentage of load carried by solar unit in all but coldest periods.

Season	1949-50	1950-51	1951-52	1952-53
Heating load of season, thousands of Btu	40,022	35,414	36,457	37,530
Percentage of load by solar system	74.1	75.0	82.3	69.0
Percentage of load by auxiliary heat	[illegible]	[illegible]	17.7	31.0

condition, of heavy heating load and poor atmospheric conditions, do not favor solar heating. Despite these limitations, the following conclusions can be drawn:

- Solar energy can be successfully utilized for space heating.

- To produce a solar energy system that will be competitive from an economical standpoint will require much more research and development work.

- The design of a solar energy system for space heating requires the closest cooperation between engineer, architect, and contractor.

- The design of the energy transport system is extremely critical and requires expert attention.

Yes, it is true that this house proved that "solar energy can be successfully utilized for space heating", technologically... But the second conclusion, that an economically competitive system will require much more research, lies at the base of the problem confronting the use of solar energy today. We have the technology and skill to use solar energy in domestic heating (and this information has to be given to the public) but unless such technology can, along with its other benefits, be made economically competitive with the traditional methods of domestic heating (and cooling), it is without much value in the solution of our energy needs.

The third conclusion, that the design of such a system requires the close cooperation of engineer, architect, and contractor is another indication that there are many problems yet to be solved and that the final product will be expensive. (such collaboration is economically expensive; perhaps one method of cost reduction is simplicity of design to require less collaboration).

The cautionary note of the fourth conclusion, that the design of the energy transport system requires great care, points to two possible problem areas. One of them is a problem which we have mentioned, that of even distribution of the water over the surface of the collector so as to more efficiently make use of the heat surface. The second problem area is that of keeping pumping costs low, the primary cost being that of electricity. The design must insure that the expenditure of electricity is more than offset by the gain in solar heat.

After 20 years of research, the solar heating team at MIT constructed a two-storey, 1450 sq ft house in Lexington, Mass., a suburb of Boston, in 1959. The solar heating system was to provide 75 to 80 per cent of the house heat as well as a large part of the domestic hot water. Its 640-square-foot collector (16 x 40 ft), tilted at 60°, consisted of two layers of glass covering a thin (.025" thick) aluminum sheet painted a heat-absorbing black. Water from the 1500-gallon storage tank (5 ft in diameter, 9 ft long) was warmed as it was circulated through copper tubes attached to the aluminum plate (figure 1) The warm water in turn was pumped through a heat-exchanger as needed to warm the air which warmed the house. An oil furnace provided the auxiliary heat. During the summer, a small tank was connected to the collector for domestic hot water and a small (3/4 ton) refrigeration compressor was applied to the large tank to provide cooling for the house (figures 2 and 3).

The researchers at MIT knew that economically solar heating might be impractical, but it was their intention to achieve a measure of success upon which to build another house, selling House IV to help finance it. That house would in turn be sold to finance yet another house. A series of setbacks forced an abandonment of this plan, however. Costs of the system were greater than anticipated, the system provided a smaller percentage of the heat required by the house (about 46%) than was predicted, and MIT found itself in the unenviable pos-

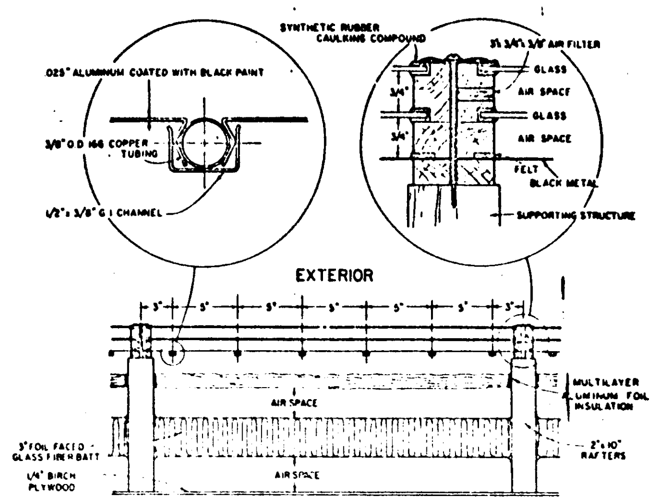


Fig. 3 A cross-section of the solar collector assembly

1 (PIS-3)

2 (PIS-2)

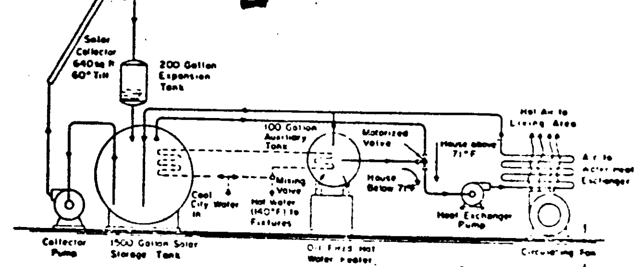
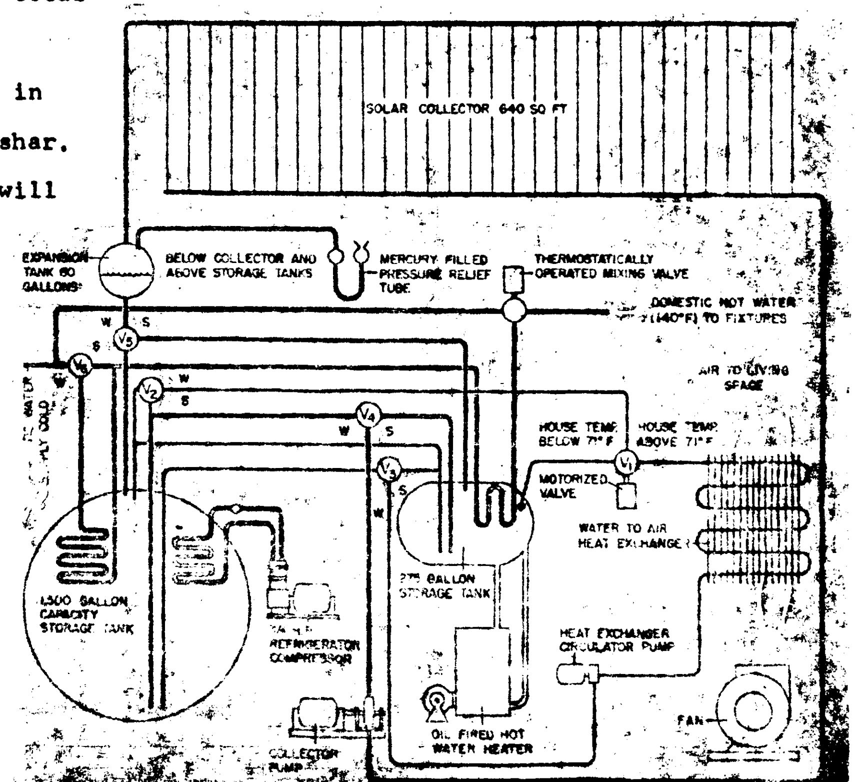


Fig. 2 A schematic diagram of the solar heating system

ition of having to provide its highly trained scientists and engineers as repairmen of a domestic heating system. Although the solar system operated fairly well, ordinary things, such as valves and gauges, failed to function properly (probably no reflection on the solar system itself).

The house's first heating season, 1959-60, was more severe than predicted and there was less sunshine than usual. The total solar incidence was 122.4 million Btu. Of this amount, 32.4 million Btu was of too low intensity to justify attempted collection and 40.9 million Btu was actually extracted from the collector and brought to the storage tank. This heat in turn provided 34.4 million Btu of the total heating load of 74.5 million Btu, or 46%.

The following 8 pages are an ASME publication, 'Progress in Space Heating with Solar Energy' by C D Engebretson and N G Ashar. This rather detailed and well-written article about House IV will give the reader further insight into the project.



3

(RRS-206)

Fig. 1 The M.I.T. Solar House IV, Lexington (42° N, 71° W), Mass.

Progress in Space Heating With Solar Energy

C. D. ENGEBRETSON **N. G. ASHAR**

The solar heated home of the present day is serving as the pilot plant in the logical development of the method by which general use of solar energy for space heating may be accomplished. The record of the performance of such an experiment during a heating season is intended for use in justifying theory, and in orienting the analytical and laboratory phases of solar-energy utilization research.

The poor correlation between solar-energy supply and space-heating demands is not encouraging; however, the performance of solar-energy collectors and the influence of weather variability has received considerable study, the reports of which permit reasonable prediction of the capability of a particular design (1, 2).[1] The art of space heating by other energy sources is well known as measured by the 20 per cent of the national energy consumption for this purpose.

The conclusion that some benefit is realizable by coupling the solar-energy collector to the space-heating system has been reached by many. The performance of a particular system in a particular environment with evidence as to how typical the environment was, during the period of the experiment, should contribute to knowledge of the validity of this conclusion.

[1] Numbers in parentheses designate references at the end of the paper.

MIT SOLAR HOUSE IV

The present MIT solar house is the fourth experimental structure built under the direction of the Space Heating Committee of the Solar Energy Conversion Project financed by funds contributed by Godfrey L. Cabot (3). The first two solar houses included laboratory facilities only, while the third was a small laboratory building remodeled to incorporate 608 sq ft of living facilities for a family of three (4). Solar House IV is unique in that it was designed as a solar house to make the fullest use of collected energy and waste as little energy as possible and at the same time meet the comfort and space requirements of modern living. Studies were made to determine the optimum form and shape of house to satisfy these requirements and give as nearly as possible optimum and practical performance. These studies indicated that a design by which it could be possible to receive a maximum of

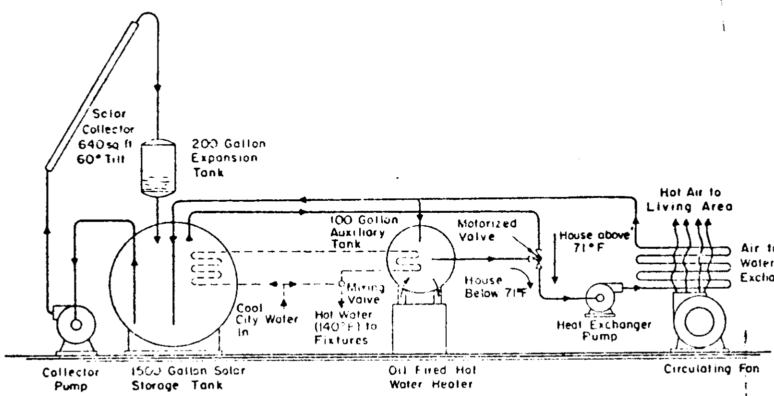


Fig. 2 A schematic diagram of the solar heating system

75 per cent of its heat from the sun was practical in the New England climate (5).

The house, Fig. 1, is of two-story design containing 1450 sq ft of usable living area. On the first-floor level are two bedrooms, bath, dining room, kitchen, entry hall, and several closets. The second-floor level contains the living room, master bedroom, bath and dressing room. Connected to the living room by a bridge is a screened porch while across the brick patio from the ground floor entrance is a carport. The design is quite different from the popular ranch or split-level house but it succeeds in its purpose of being comfortable and convenient. The south elevation of the house above ground level consists entirely of 640 sq ft of solar collector sloping at an angle of 60 deg to the horizontal.

The house is of frame construction above ground level, built of first-quality materials and well insulated throughout. Except for the back of the collector, which is heavily insulated to prevent excessive back loss, the insulation does not exceed the amount which should be considered good building practice in this climate. All windows are thermopane or double glazed and doors and movable sash are weather stripped. The terrain has been manipulated so that the major portion of the side walls of the first floor are below grade to minimize heat loss in this area.

ENERGY COLLECTION SYSTEM

The system for collection and storage of solar energy is that portion of the schematic diagram, Fig. 2, comprising the collector, 200-gal expansion tank, 1500-gal storage tank, collector circulating pump and connecting piping. The collecting surface is made up of 0.025-in-thick and 4 5/8-in-wide aluminum elements mechanically attached to 5/8-in-OD copper tubes on 5-in. centers by clip channels. This assembly with two layers of cover glass spaced 3/4-in. apart is shown in cross section in Fig. 3. Two coats of flat-black paint on the outer surface of the aluminum and copper-tube assembly produces an absorptivity originally equal to 0.97 by measurement. Low-iron-content glass is used for maximum transmittance of solar radiation. The back of the collector, which is common with wall and roof of the living space, is insulated with a 3-in. layer of foil-faced fibrous-glass insulation and a 4-in. air-space layer of multiple reflective insulation. The hydraulic circuit is completed with appropriate piping as indicated in Fig. 2. Both the expansion tank and the 1500-gal storage tank are heavily insulated with loose-fill-type insulation. The energy transport and storage medium is water.

HEATING SYSTEM

The heating system of the solar house is somewhat more complex than conventional systems. It must provide the means of removing energy from storage and introducing it as heat into the living space on demand. It must also include a means of introducing energy from an auxiliary system when the solar energy in storage is exhausted or incapable of satisfying the demand and be endowed with sufficient intelligence to make the decision when this operation is necessary. It should further be chosen to transfer heat to the living area with a minimum temperature difference because of the sensitivity of

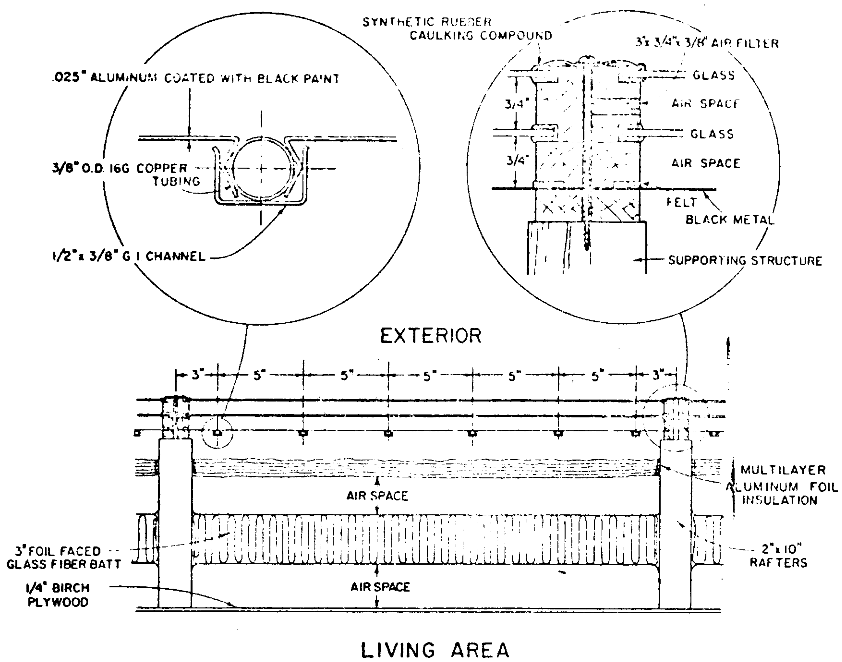


Fig. 3 A cross-section of the solar collector assembly

solar-collector-efficiency to energy-storage-tank temperature.

To satisfy the last of these requirements a forced-hot-air system was chosen with a water-to-air heat exchanger, larger than that corresponding to conventional practice.[2]

The water-to-air heat exchanger in the air-distribution system of the house and the circulating-pump blower are shown in Fig. 2. The oil-fired water heater and motorized valve comprise the auxiliary unit and its connection with the main system. With this design of solar heating system some economic benefit is realizable by use of heat from the solar storage tank down to a tank temperature of approximately 84 F.

Control is accomplished by a two bimetal room thermostat and thermostats in the solar-energy storage tank and in the tank of the oil-fired auxiliary tank.

A means of heating domestic hot water is provided by coils submerged in the solar-energy storage tank and in the auxiliary unit. A thermostatic mixing valve tempers hot water in the event the solar-energy storage-tank temperature is beyond the temperature level which can be used safely at appliances and outlets throughout the house.

INSTRUMENTATION

Correlation of the performance of this house with the theory upon which the design was based depends upon obtaining sufficient data to construct an energy balance. For this reason suitable instrumentation was provided to obtain continuous solar-radiation measurements in the 60-deg plane of the solar collector and on a horizontal plane. Total radiation pyrheliometers and strip-chart recorders are used in this service. Water meters were included in the collector energy-transport circuit, domestic hot-water system, and heat-exchanger water circuit to measure integrated water flow. Separate power meters and operating time meters were included in the electrical services to each motor in the system. A total of 28 separate temperatures were recorded continuously by multipoint strip-chart recorders. One strip-chart recorder is used to record the temperature difference in the transport stream across the collector. Fuel-oil consumption is determined daily and readings of the other meters recorded at the same interval.

One of the merits of water as an energy transport and storage medium is the ease with which energy-balance determinations can be made

[2] Experience with radiant ceiling panel heating in the MIT Solar House III (4) indicated the higher temperature difference necessary to transfer heat to the living area.

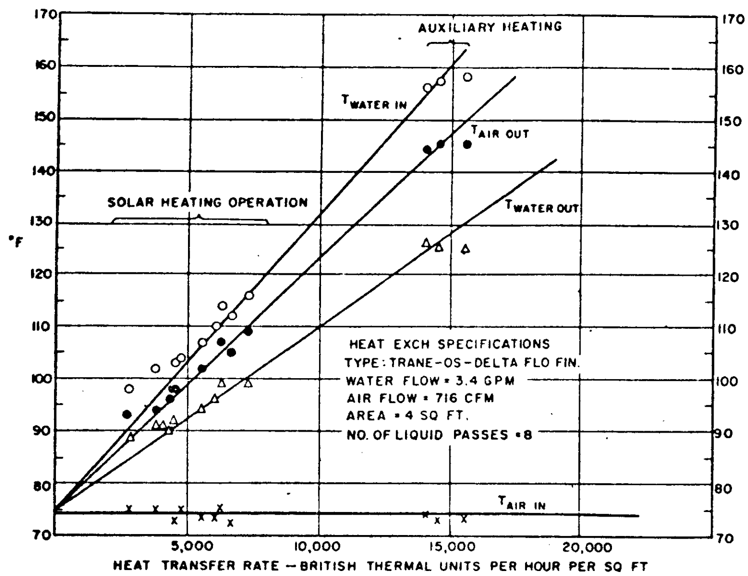


Fig. 4 Heat exchanger characteristics

and energy quantity in storage assayed. Knowledge of flow, time, and temperature permit analysis of the performance of any particular hydraulic circuit of the system.

MODE OF OPERATION

Human comfort is the primary purpose of any heating system whether it be solar or otherwise. The heating system and the control thermostat were adjusted to suit the comfort requirements of the occupants. No attempts were made to alter individual habit patterns to favor the means of heating. For example, it is possible to favor the solar heating system by scheduling high demands for domestic hot water at the time of day when the storage unit is at its highest temperature thereby reducing the amount of auxiliary heat required for "topping up" this demand. However, this was not done and dish and clothes-washing operations were carried out at the convenience of the housewife. No "night set back" of the thermostat was used and lower temperatures in sleeping areas were accomplished by manipulation of duct damper settings and by ventilation. The return-air temperature to the heat exchanger remained in the range of 73 to 75 F throughout the heating season.

HEATING-SYSTEM OPERATION

Heating-system operation is initiated by the first-stage bimetal in the room thermostat, which causes the heat-exchanger circulating pump and blower to operate. Water is pumped from the top of the 1500-gal storage tank through the heat exchanger and returned to the bottom of the tank. Return air from the living space is passed through a filter bank and the heat exchanger and redistributed to the house. When the demand for heat is greater than supplied by the heat exchanger, the living space will continue to cool. At the temperature 1 deg less than that necessary to close the first-stage bimetal, the second-stage bimetal will cause the motorized valve to operate causing the circulating pump to take hot water from the oil-fired auxiliary system through the heat exchanger and return it to the auxiliary tank. The water in the auxiliary system is maintained continuously at a temperature of from 145 to 160 F. This temperature is more than adequate when supplied to a heat exchanger having a UA of 1800 Btu/hr deg F at a water flow rate of 3.4 gpm to satisfy the maximum demand of the house. Air flow through the heat exchanger is 716 cfm with average air-filter conditions.

When high demands beyond the capability of the solar-energy storage are satisfied the system returns to operation with this source of heat. Fig. 4 shows the water temperature and heating-capacity relationship of the system, and indicates a heat-exchanger efficiency of 83 per cent (ratio of air-temperature rise to maximum possible rise, using a heat exchanger of infinite surface). For a given demand it is

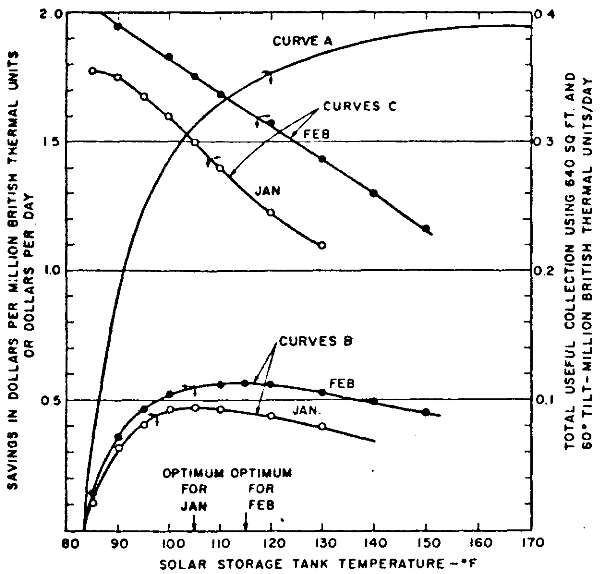


Fig. 5 Economic study of influence of the storage tank temperature on the savings in operating costs. Curve A: Operating cost savings in \$/million Btu delivered to the living area due to use of solar heat instead of oil heat. Curve B: Operating cost savings, \$/day due to use of the present solar heating system in a given month. Curve C: Total useful collection using 640 sq ft at 60° tilt with a given monthly average air temperature in million Btu/day. (Air temperature used for these curves were 31° F in January and 36° F in February)

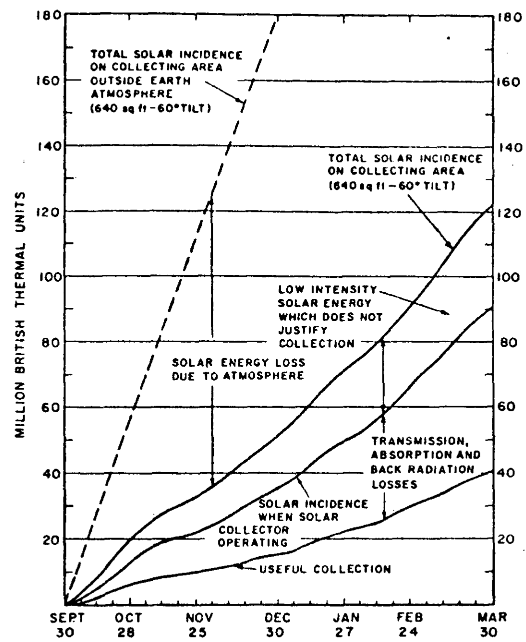


Fig. 6 Solar collector performance during the winter season 1959-1960. Cumulative values for every week are plotted in million Btu

possible from this diagram to ascertain the minimum storage temperature which will satisfy the demand and the point where any subsequent reduction in storage-tank temperature or increase in demand will cause a change over to auxiliary operation. A thermostat is provided in the solar-energy storage tank which can be adjusted to prevent operation which would be economically unfavorable. Domestic hot-water use averages 85 gal per day and is heated from city water temperature of about 50 F during the heating season to approximately the temperature of the solar-energy storage in passing through the coil in the 1500-gal tank. It then passes through the coil in the auxiliary tank for further heating to temperatures in the range of 140 to 155 for distribution throughout the house.

A word is in order on the choice of solar storage-tank temperature. Assume that, for a given month, the space-heating requirements exceed the collector performance as to permit every Btu collected from the sun to be used. The economic optimum storage-tank temperature can then be determined as shown in Fig. 5. The cost per million Btu delivered to the living area is first calculated for the solar and the oil-heating systems. The operating costs consist of the power costs at 3¢ per kwhr to run the collector pump (operating time based on a long-term average of 63,000 Btu/hr collector operation), to run the heat-exchanger pump, air blower and oil burner, and the cost of fuel oil at 15¢ per gal. The difference of these costs, the excess of fuel-heat cost over the solar-heat cost, is plotted versus the solar storage-tank temperature in curve A. The increase in savings with rising tank temperature is due to the reduced heat-exchanger operating time to deliver a million Btu to the living area. But, allowance must be made for the fact that the collection efficiency increases as the storage temperature decreases, the outside air temperature being constant. The useful solar-energy collection can be estimated as shown by Hottel and Whillier (2) by the use of the ∅ or utilizability curves. Calculations were made for useful collection in millions of Btu per day versus storage-tank temperature using a flat-plate collector of 640 sq ft area and 60-deg tilt in the Boston area during the months of January and February (see curves C). For a given storage-tank temperature, the daily savings in operating

TABLE 1 DEGREE DAYS PER MONTH (65 DEG F BASE)

Month	Solar House IV 1958-59	Solar House IV 1959-60	Blue Hill(7) 1958-59	Blue Hill(7) 1959-60	Boston 1958-59	Boston 1959-60	Normal(7)
October	540	339	488	420	386	319	315
November	623	735	691	716	547	611	618
December	1164	1140	1316	997	1190	855	998
January	1058	1395	1234	1163	1118	1048	1113
February	1046	1073	1148	943	1065	855	1002
March	843	1116	972	1108	862	992	849
Total	5274	5798	5849	5347	5168	4710	4895

cost is the product of the useful collection in million Btu per day and the savings in dollars per million Btu transferred to the living area using the present solar-heating system. This daily operating savings for the months of January and February appear in curve B, Fig. 5. The economic optimum tank temperature for January and February are 105 and 115 F, respectively. Similar calculations could be made for other months but the flatness of the optimum indicates that 110 F is adequately near the seasonal optimum.

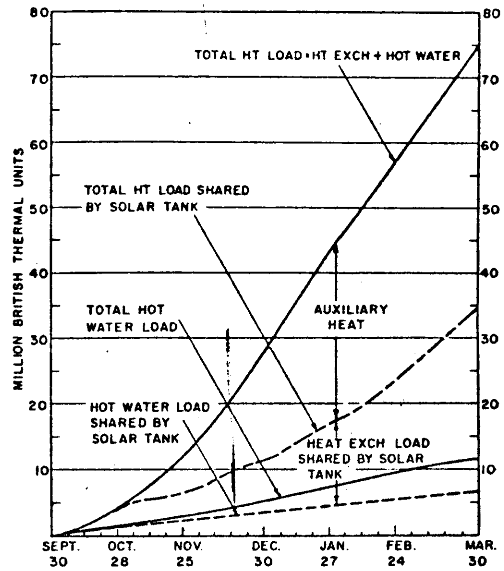


Fig. 7 Solar House IV performance during the winter season 1959-1960. Cumulative values for every week are plotted in million Btu

ENERGY-COLLECTION-SYSTEM OPERATION

The operation of the collector circulating pump and consequently the on-off cycling of the collector is controlled by a pair of sensors one of which is in the energy-storage tank, the other in the collector proper. These sensors are resistance elements in the legs of an a-c bridge circuit, the unbalance of which actuates an electronic relay. This bridge-and-relay combination is adjusted so that radiation on the collector sufficient to cause approximately a 5-deg F temperature rise in the water-transport stream through the collector, operation is initiated. When radiation is inadequate to cause a temperature difference of more than 3½ deg F collection is terminated. A temperature rise of 1 deg F is the "break-even point" at the present cost of electrical energy to drive the pump. A somewhat higher than "break-even" differential at start of collection is desirable to prevent any short cycling or nervous operation of the control and pump. Present water-circulation rate through the collector is 8.2 lb/hr sq ft.

The water automatically drains from the collector at the completion of each collection cycle and is replaced by air from the top of the expansion tank. This feature is extremely desirable in a solar collection system to reduce losses during cold cloudy periods and to reduce freezing hazards. It is also the cause of the most difficult single operational problem of the system, that of air entrainment in the transport system. Considerable experimentation was necessary before a system capable of returning this entrained air from the points where it was disengaged from the liquid to the expansion tank was devised. The average power cost of collecting one million Btu was 17.5 cents.

RESULTS

The system and house herein described has, during this past season, demonstrated a capability for providing a high degree of human comfort during a period of abnormal heating demand and subnormal solar radiation. Table 1 shows a comparison of degree-days data from near by reporting weather stations and that taken at the solar house. There exists a discrepancy due in part to a difference in the method of interpretation of the weather bureau and the solar-house data, in computing average temperature and degree days. The weather bureau stations assume a normal distribution of temperature around the arithmetic mean of high and low temperature for a day while the solar-house degree day is based upon average of measurements of air temperatures recorded at 8-min intervals. When normal distribution exists there is no difference due to the method, but January 1960 shows that the distribution was somewhat skewed. Comparison of data with an air-base weather group, 2½ miles away, has shown that by adopting the weather-bureau system, the data are comparable to the extent that differences are those normally expected considering site, exposure, and elevation. However, it is felt that the method used here more clearly represents the climatic conditions surrounding the experiment. Boston weather was warmer during this heating season than the long term normal, but, the season was more severe on the site than the previous season when Boston was very near normal. Blue Hill data as given in this tabulation show the same trend as Boston. The one fact demonstrated clearly is that in the temperate zone near a large body of water, the variations in weather over a short distance as one moves inland such as the 19 air miles to Blue Hill and the 15 miles to Boston, can be very great. Temperatures taken on the site, therefore, have been used in the calculations of heat load.

Cumulative diagram, Fig. 6, shows that of 122.4 million Btu incident on the collector during the season October 1959 through March 1960, 90 million Btu were received during periods of collection of which 40.9 million Btu were collected and transported to storage. Very apparent is the plateau in the curve during November 1959 which was especially low in usable sunshine. Collector efficiencies have been above 40 per cent throughout the season, resulting in a long-term average efficiency of 45.4 per cent. Cumulating diagram Fig. 7 shows the use of the collected solar energy for space heating and domestic hot-water demands. Forty-four per cent of the space-heating load and 57 per cent of the domestic hot-water load were borne by the solar-energy system. This results in a 46.1 per cent sharing of the total heating load during the season. The monthly values are given in Table 2. At all times sufficient energy to accomplish the domestic hot-water heating duty was in storage. However, its level was rarely high enough to eliminate second stage of "topping up" heating in the auxiliary unit, hence the high percentage of this load by auxiliary means. The seasonal economic storage temperature of 110 F, as indicated earlier, will always necessitate auxiliary water heating means regardless of the size of the collector.

This summary includes only that heat intentionally transferred to the living space metered and controlled. System losses which occur within the structure contribute an unmetered amount.

Contributions to the heating load of this house from sources other than the heating system proper can be classified as those of a normal residence plus those peculiar to a solar house. The average home experiences heat supplied by occupants, lighting, appliances, and solar radiation on the structure and through the windows. In addition to this the solar house receives a contribution from the back wall of the collector and the thermal losses from the energy-storage unit within its envelope. The extent of the contribution from the energy storage or from the back wall of the collector has not been fully explored. However, experimental results indicate they exist. During operation of the collector at temperatures considerably higher than room temperature, heat transfer to the living space is observed. During periods when the solar collector is not active because of inadequate radiation to permit economical operation, diffuse radiation observed will cause the collector to achieve a temperature high enough to accomplish some heating or to some extent retard if not totally eliminate the heat loss to the outside air from this portion of the enclosure.

A portion of thermal losses from the 1500-gal energy storage tank are to the basement floors and walls and consequently directly to the earth but an equal amount of surface area of the tank enclosure is exposed to basement air.

TABLE 2 ENERGY BALANCE ON SOLAR HOUSE IV (WINTER 1959-60)

No.		October	November	December	January	February	March	Total
1	Total 60° incidence* on 640 ft²	21.6	12.4	16.7	21.8	21.7	28.2	122.4
2	60° incidence when collector pump is operating	14.6	8.3	11.7	16.5	16.7	22.2	90.4
3	Total collection	6.3	3.5	5.5	7.4	8.1	10.1	40.9
4	Energy to heat exch. by solar heated tank	3.1	1.5	3.5	5.0	6.1	8.4	27.6
5	Energy to domestic hot water by solar heated tank	1.5	0.8	1.0	1.1	1.2	1.2	6.8
6	Total energy supplied by the solar heated tank	4.6	2.3	4.5	6.1	7.3	9.6	34.4
7	Solar tank losses	1.7	1.2	1.0	1.3	0.8	0.5	6.5
8	Energy to heat exch. by auxiliary	0.0	6.2	9.0	9.0	5.8	4.9	34.9
9	Energy to domestic hot water by auxiliary	0.1	0.7	1.0	1.1	1.2	1.1	5.2
10	Total energy supplied by the auxiliary	0.1	6.9	10.0	10.1	7.0	6.0	40.1
11	Total heat exch. load	3.1	7.7	12.5	14.0	11.9	13.3	62.5
12	Total domestic hot water load	1.6	1.5	2.0	2.2	2.4	2.3	12.0
13	Total heat load	4.7	9.2	14.5	16.2	14.3	15.6	74.5
14	% of domestic hot water load shared by solar tank	94	53	50	50	50	52	57
15	% of heat exch load shared by solar tank	100	20	28	36	51	63	44
16	% of total heat load shared by solar tank	98	25	31	38	51	62	46
17	Predicted % of total heat load shared by solar tank (5)	100	84	68	56	73	87	75

* All values in million Btu

Heating of the basement and consequently the lower floor somewhat reduces the demand on the heat exchanger.

Examination of data on the behavior of this structure indicates that during periods when the intensity of solar radiation exceeds 150 Btu/sq-ft hr, no heating-system operation was required until the temperature difference between the living space and the outside air exceeded 14 deg F. When the solar incidence is less than this value, heating-system operation was generally required when the temperature difference across the walls exceeded 10 deg F. Since the periods of incidence below 150 Btu/sq ft hr greatly exceed those of higher solar incidence, heat-load estimates have been made neglecting the first 10 deg of temperature difference.

The experimental data yield a combined UA-value for the house of 500 Btu/hr deg F when fitted into the following expression for heat load:

$$Q = (t_1 - t_o - 10)\ 500$$

where

Q = hourly heat loss, Btu/hr

t_1 = inside air temperature, deg F

t_o = outside air temperature, deg F

500 = UA = heat-loss coefficient and area product, Btu/hr deg F

Using this experimentally determined UA-value in the expression for the heat load of this house it is possible to work backward and roughly evaluate the contribution from the solar-energy-system components. One concludes there is no net gain from insolation through the windows and radiation on the structure during the day because of an equal amount of back radiation during the night, if one makes an evaluation by hand-book methods (5). Electrical power used averages about 750 kwhr per month. This amounts to about 3555 Btu/hr which when added to the probable 1500 Btu/hr for occupancy by three persons and considering the UA-value of 500, accounts for the lack of heat requirement for the first 10 deg of temperature difference. The low UA-value of 500 Btu/hr deg F can be attributed to energy losses in the envelope from components of the solar-heating system. The collector-back contribution during periods of low incidence is negligible. The collector-back loss and miscellaneous radiation gain contribution during periods of incidence greater than 150 Btu/sq ft hr can then be assumed to be the factor in the 4 deg greater temperature difference before heating is required. Hence, the total miscellaneous radiation and collector-back-loss contribution averages 2000 Btu/hr during these periods.

CONCLUSIONS

1 The degree of comfort realized was independent of the type of heating system and the combination of solar and auxiliary systems are workable to achieve this end.

2 Auxiliary heating systems are required in the northern latitude to provide satisfactory domestic hot-water temperature.

3 Special considerations are required in designing the hydraulic circuit for the solar-energy collection system owing to the presence of air and water. Air transported to the components of the system other than collector and expansion tank can reduce the rates of water flow and heat transfer.

4 The thermal performance of the collector was in good agreement with the theoretical calculations.

5 The construction of the collector assembly was simplified by the mechanical attachment of tube and aluminum plate with the clip channels. No loss in the heat-removal efficiency was observed in spite of the reduced contact area.

6 It would be desirable to have degree days computed on weighted average air temperatures rather than arithmetic mean of maximum and minimum.

7 The economical seasonal operating storage-tank temperature was about 110 F for the present solar heating system.

8 It is logical to expect the system to share a greater fraction of the total yearly heating load than realized during the 6-month test period. This period was deficient in solar radiation and included more severe weather conditions than normal.

ACKNOWLEDGMENT

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1 H. C. Hottel, and B. B. Woertz, "The Performance of Flat-Plate Solar Heat Collectors," Trans. ASME, vol. 64, 1942, pp. 91-104.

2 H. C. Hottel, and A. Whillier, "Evalua-

Dr. Maria Telkes, engineer, along with Miss Eleanor Raymond, architect, and Miss Amelia Peabody, philanthropist, built a solar-heated house in Dover, Mass (independent of MIT's work) based on the notion of complete heating by solar energy. The nine days of heat storage was attained by using Glauber's Salt (Na_2SO4, $10H_2O$) as the storage medium (60 lbs per sq ft of collector). The heat of fusion (or 'heat of transformation', solid-liquid-solid) of this material is 104 Btu per lb. Its density is 92 lb per cu ft so that one cubic foot of this chemical can, theoretically, store 9500 Btu at its melting point, which is about 90F. In the temperature range of 80-100F, a cubic foot of water stores 1300 Btu through the specific heat effect. The salt through the same range stores 1500 Btu in specific heat in addition to its heat of fusion (9500 Btu) for a total of 11,000 Btu per cu ft. (SHH - 72)

The advantages of the salts are clear. Not only do they store seven or more times more heat per volume than substances relying on specific heat, but they can collect and store the heat at a relatively constant and moderate temperature. Its primary drawback has proven to be more than this house or subsequent work since has been able to solve; the chemical salt stratifies in its container resulting in imperfect reversibility between liquid and solid. The Dover house was converted to standard heating.

(SHSE - 396)

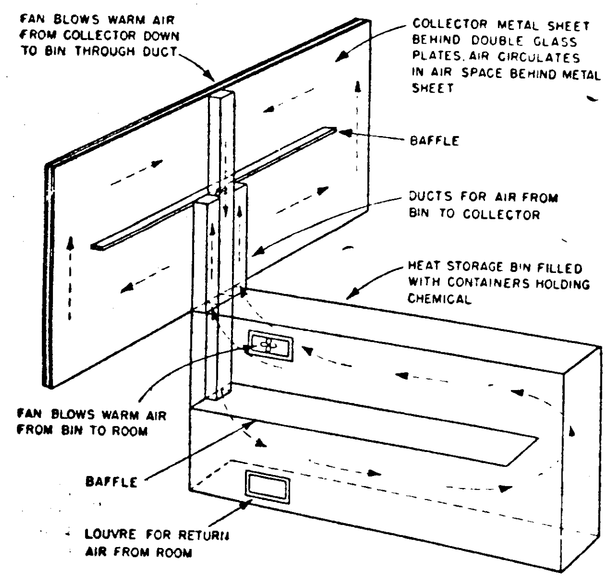


FIG. 1. Heating system, sun-heated house, Dover, Mass.

Dr. George O G Löf has been one of the foremost pioneers in the field of solar energy use. Prior to 1950 he designed a collector and applied it to an existing five-room, 1000 sq ft, bungalow in Boulder, Colorado. The primary objective in the design was "the maintenance of simplicity and economy in construction and the development of a collector suitable for large-scale factory production." (SHW)

> The solar collector unit (figure 1) consists of a sheet metal trough approximately 3 in deep, 2 ft wide and 4 ft long containing a series of single-strength glass plates arranged in a stair-step fashion and separated by ¼ in spaces. Each pane of glass is 24 in wide, 18 in long and blackened with black paint or a black glass coating in an area 6 in by 24 in. The glass is arranged so that each black surface is beneath two clear surfaces. One or more single-strength cover glasses 2 ft by 4 ft in size are supported on the top edges of the trough and form a nearly air-tight enclosure containing the overlapped plates. By means of this arrangement, solar energy is transmitted through the transparent surfaces and absorbed in the black areas; the 'greenhouse effect' causes the black surfaces to reach a relatively high temperature. (SHW)

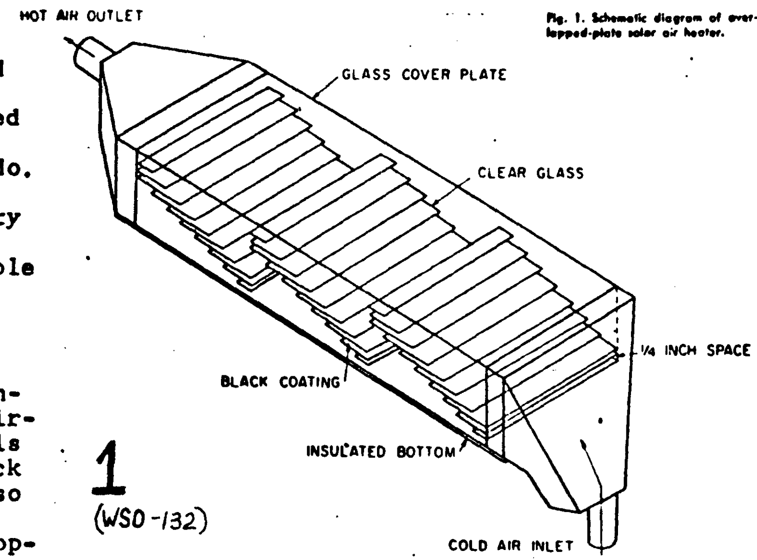


Fig. 1. Schematic diagram of overlapped-plate solar air heater.

1 (WSO-132)

Air to be heated enters the lower end of the trough at a low velocity and exits at the upper end at temperatures approaching that of the black areas. Löf has found that best performance results when the air encounters four sets of glass plates between entering and leaving the trough.

Efficiency of heat collection ranges from 30 to 65 percent; as air velocity increases, efficiency rises but exit air temperature decreases. Fifty percent efficiency is obtained at an air-flow rate of 1.6 cu ft per sq ft of collector surface. With surface-treated low-reflective glass and two cover plates this efficiency increased to 59 percent.

For the Boulder house, a collector of 463 sq ft was mounted on the roof (facing south at a 27 degree angle with the horizontal) and separated from the shingles by a one-half inch layer of celotex insulation. The 180 cu ft basement storage bed consisted of 8.3 tons of 3/4 in gravel. Warmed air from the collector was gathered at the roof ridge and was transported to the storage. It passed through the bed to return to the lower end of the collector, becoming cooler as it transferred its heat to the gravel. Figure 2 shows the heating system.

Costs of the system were difficult to determine and would be almost meaningless because of the experimental nature of the project. In its first season of operation, the solar unit supplied 25.6 percent of the heat, and the fuel savings "should have been at least $20.oo or 32 percent" (this in 1950). (WSO - 137)

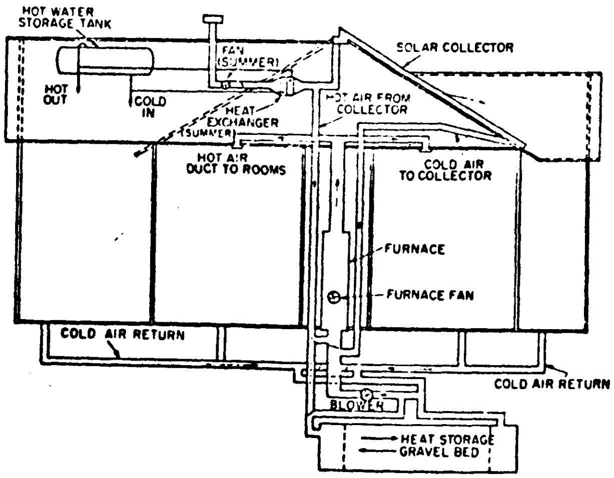


Fig. 5. Schematic diagram of solar heating system in Boulder House.

2 (WSO-135)

DENVER HOUSE

George Löf found from his experience with the Boulder house that it was practical to combine solar heating with an existing conventional installation. His next step was to plan and construct "an entirely new and modern house heated by an improved solar heating system and (to test) the house under actual living conditions." (WSO - 137)

The house originally conceived was called "Denver Design" and had the solar collector as an integral part of the house roof. After considerable planning and preparation (figure 1), construction was delayed in favor of the possibility of incorporating solar cooling, which had yet to be adequately developed. Construction of what was now called the "Denver House" was then scheduled for 1956, in Denver.

The main attitude difference from the Denver design was that it was felt that "the house should be convenient for application of a solar heating system which could be added to it as an appliance or a piece of equipment rather than being made an integral part of it." (WSO - 142) The house was thus designed with a flat roof on which were placed two banks of sloping (45° angle) solar collectors, each 6 ft high and 50 ft long for a total collector area of 600 sq ft.

The one storey, "contemporary" home of 2100 sq ft, designed by James Hunter of Boulder, had many features for collecting heat and keeping it inside the house, among them, south-facing windows; reflective-lined draperies; and shoji screens on the west designed to act as one-way mirrors that can be reversed to reflect heat outward or to re-

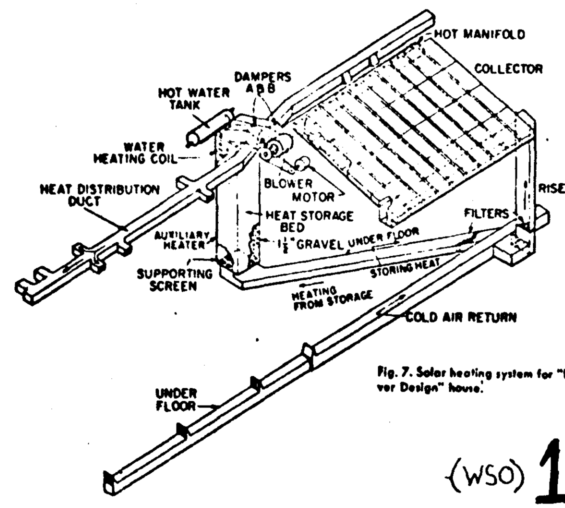


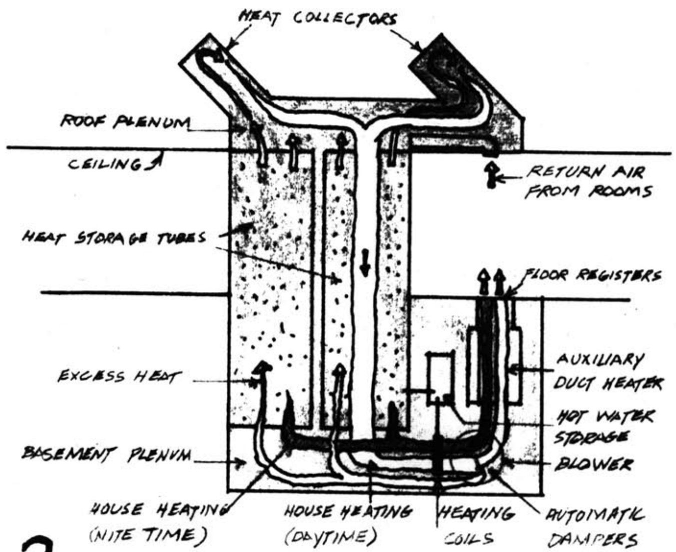
Fig. 7. Solar heating system for "Denver Design" house.

(WSO) 1

tain heat inside.

The collectors were based on the overlapped-plate principle of the Boulder house. The heat was stored in two columns of 1.5 to 2.0 in gravel. Each column was 3 ft in diameter and 18 ft high for a total of about 12 tons of rocks. The house had a heat loss rate between 20,000 and 25,000 Btu per degree day. During the winter of 1959-60 this system provided 26 percent of the heating load plus a portion of the heat needed for domestic hot water. (It was predicted however that the system would provide 60 to 70 percent of the load, and this may account for there being no more houses built by George Löf).

Figure 2 shows the heat flow diagram. Solar-heated air is drawn through a duct inside one of the storage cylinders and supplied to the bottom of the storage bed for flow up through the gravel and return to the collector. This flow is automatically diverted when rooms require heat. When the system is not collecting heat, house air flows down through the heated gravel, then to the rooms. If this air is not warm enough, the auxiliary duct heater increases its temperature.



2 FLOW DIAGRAM (RRS - 205)

THE DONOVAN AND BLISS HOUSE

Raymond and Mary Bliss (of Donovan & Bliss, Amado, Arizona) completed a 100 percent solar space-heated installation in 1954. The system was attached to a small, 25-year-old cheaply-built frame structure called the Desert Grassland Station 30 miles south of Tucson.

The primary purpose of the installation was a "stepping stone towards design of a complete solar air-conditioning system, capable of high-quality performance the year around." (WSO - 151) Of secondary importance was the desire to show that a house could be heated entirely with solar energy according to design calculations.

The collector-storage system, for financial reasons, was separate from the house. The collector uses four layers of black cotton screens, spaced ½ in apart, through which air is passed, absorbing the incident sunshine. The air is then passed through a rockpile, the heat from the air being absorbed by the rocks (figure 1).

The collector, 34 ft long and 10 ft high, has an exposed glass area of 315 sq ft and is tilted to face the midday sun squarely on 15 January. The cotton screens are probably much less durable than black-enameled metal screening would be. On a clear day the collector collects about 315,000 Btu, or about 1000 Btu per sq ft. This is twice the average daily heat requirement of the house.

The 1300 cu ft rockpile holds about 65 tons of 4-inch diameter field rock, and has a heat storage capacity of about 27,000 Btu per degree F.

For summer cooling, cool night air is drawn through a large horizontal porous screen exposed so that it loses heat by net radiant exchange with the night sky and forced through the rockpile (figure 2). Performance is better than that produced by the conventional evaporative cooler but not comparable to the comfort level attainable by high quality refrigeration systems.

Operating cost of the cooling system is about the same as that of an evaporative cooler, but the heating system operates at about $70 savings over a conventional system (utilizing butane). Although the total cost was $4000, a more realistic estimate for a house (up to 1500 sq ft) designed for it would be between $2000 and $3000, or about $1500 over the cost of a conventional heating and cooling system. Such an installation might show a fuel savings of $100 per year (1954 prices).

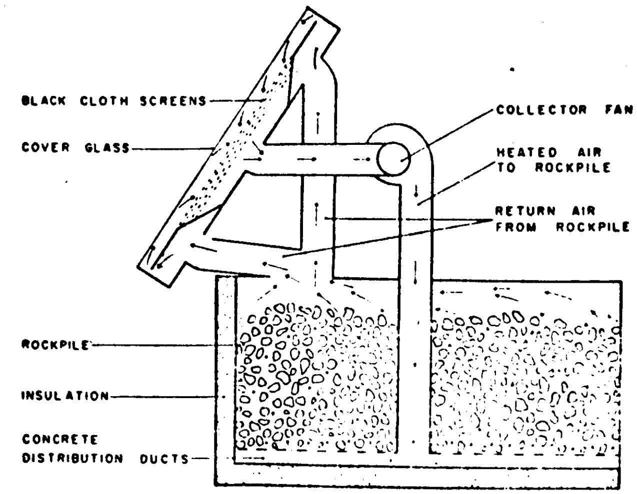


Fig. 4. Schematic view of air-heating collector and heat-storage rockpile.

(WSO-153) 1

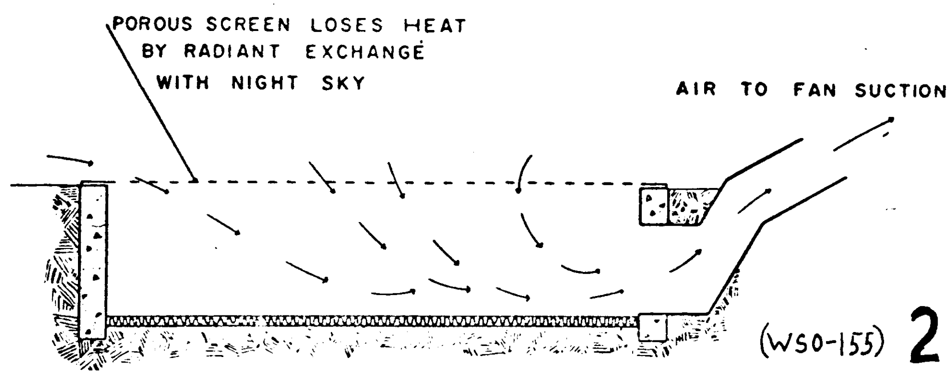
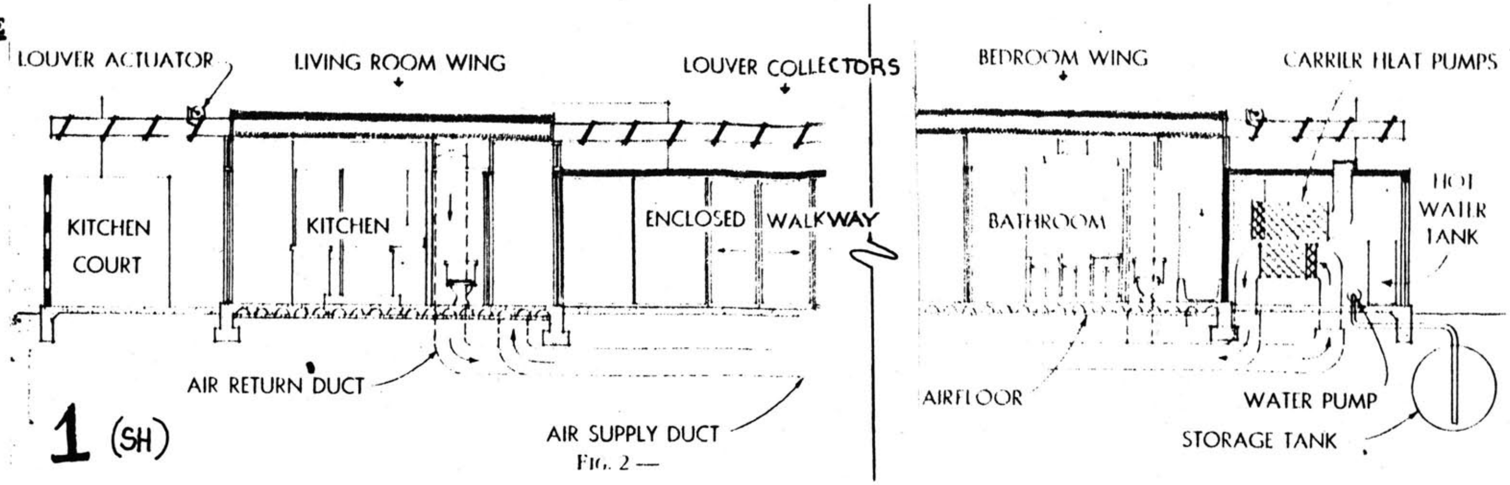


Fig. 7. Schematic arrangement for air cooling "night radiator."

(WSO-155) 2

AFASE SOLAR HOUSE

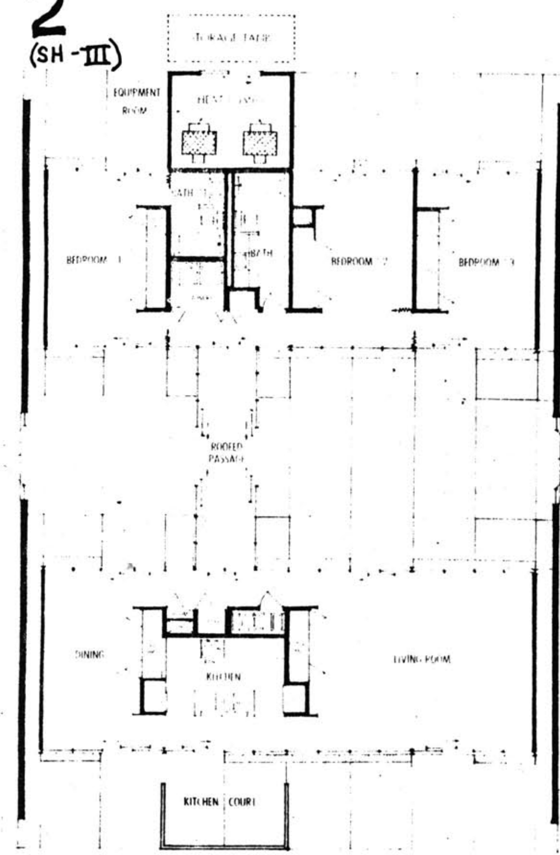


1 (SH)

FIG. 2 —

FIG. 1 — Floor plan of the Solar House.

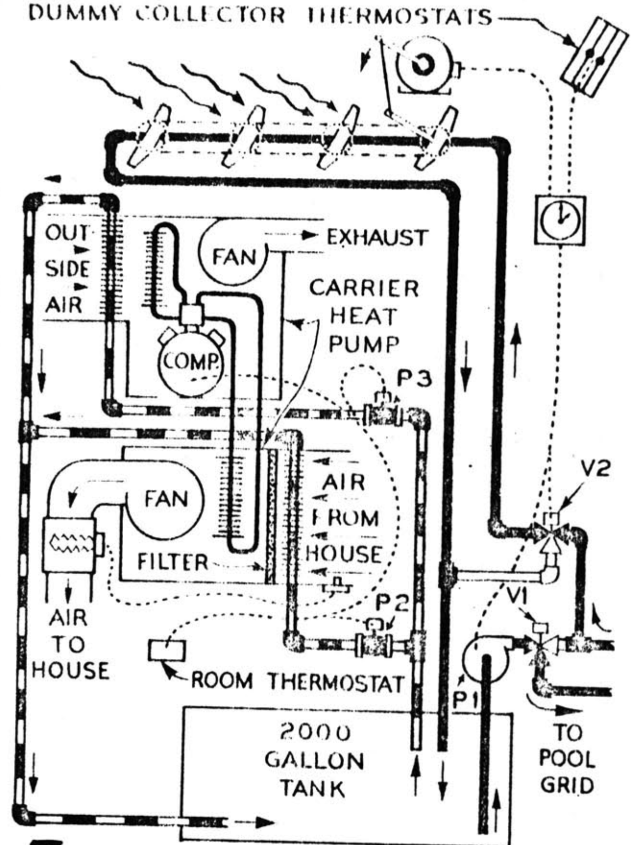
2 (SH-III)



The Association for Applied Solar Energy (now the Solar Energy Society) and the Phoenix Association of Home Builders held an architectural competition for a solar house which was completed in 1958. Peter R. Lee, a student at the University of Minnesota, won the competition and affiliated himself with Robert L Bliss, architect. Construction funds were made available by G Robert Herberger, a Founder-Director of the AFASE.

Figures 1 and 2 show a section and a plan of the house. The collector plates consist of 68 louvers in 17 parallel rows and collect heat for the house, for the swimming pool, and for domestic hot water. Figures 3 through 6 show details of the louvers, which also shade the southern exposed glazed areas during the summer (of course, they also do this during the winter as well). Note that the louvers rotate on swivel joints to follow the sun. A 2000-gal tank is insulated with four inches of fiberglass and buried in the earth. Heat pumps convert the stored water to useful house heat even when it has reached low temperatures. For summer cooling, the task of the heat pump's compressor is made easier by "circulating cool water from the storage tank through the coils ahead of the condensers. The heat thus added to the water is transferred to the swimming pool, where it is dissipated by oversize sprays." (SH - 5) Figure 7 schematically diagrams the system.

Cost data on this house is hard to find. However, Tybout and Löf (SHE) and others have shown that it is never economical to design a solar system to provide 100% of the heating capacity, as this house has done. Tybout and Löf also showed that such a system in Phoenix must provide heat at a cost approximating \$2.00 per 10^6 Btu. Judging from the complexity of the collector construction and of the system design, as well as from the low demand which the Phoenix climate puts on such a system, it is doubtful that this solution to solar heating is economically competitive with gas and oil. It must be kept in mind however that the system also provides summer cooling, domestic hot water, and a heated swimming pool. The architectural design and the collector design offers possible directions for explorations into alternatives to the large, single expanse of a flat plate collector. Solar systems are also pollution-free, are clean in operation, and have no waste products.



7 — Schematic diagram of heat pump and solar energy collection system. (SH - VI)

FIG. 6 -- Exploded view of typical collector.

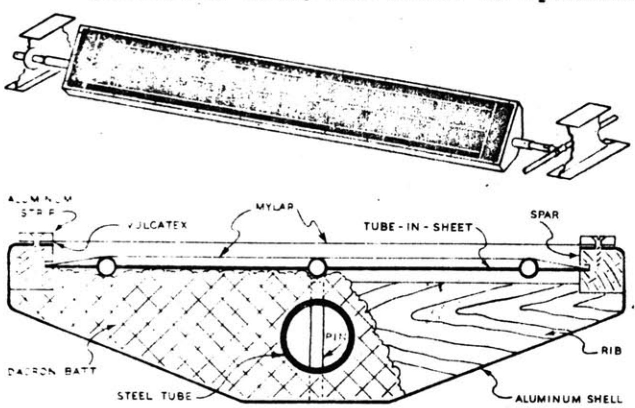
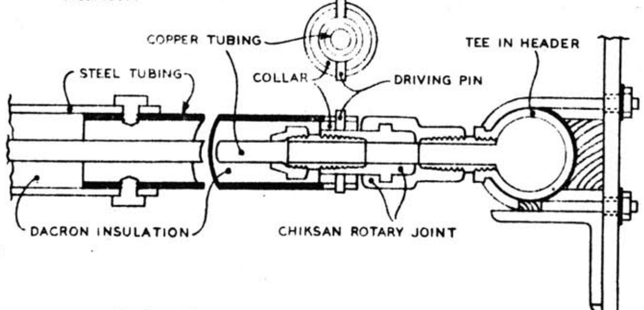
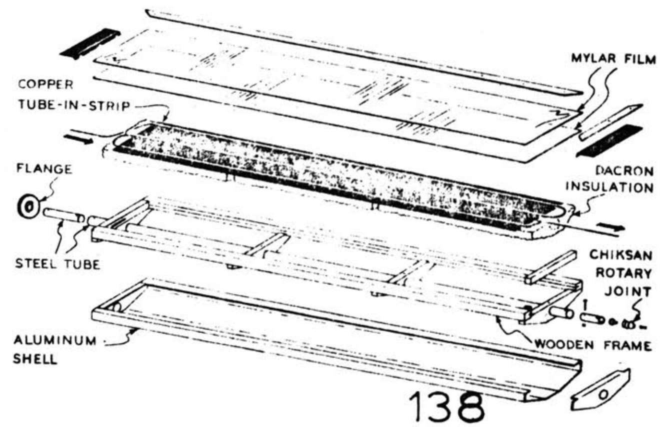


FIG. 5 — Louver end detail, showing method of connecting to headers.





3-6 (SH - IV,V)

Harry Thomason, a physicist, lawyer, inventor, and do-it-yourselfer from Washington DC, has been trying to solve the solar heating/cooling problem for 13 years. The simplistic designs of his collectors and of his heating/cooling systems and the lack of cost data and system performance data made public have left his work open to skepticism. However, he does seem to have achieved two goals of solar systems, one of constructing an inexpensive, easy-to-build collector and the other of keeping the entire heating/cooling system free from complexity.

Mr Thomason has built four solar houses and has many patents on his designs (his solar heating system is called the Thomason Solaris System). His first house, of medium size, was constructed in Washington DC in 1959. The first winter required only $4.65 of auxiliary oil heat. Without the use of the sun, the house would have needed $100 to $125 worth of oil. The 840 sq ft collector and the five-day storage tank cost $2500.

An article by Mr Thomason in 1965 evaluating the first house reports that "no major flaw in design or construction has shown up." (EWS - 17). There were a few leaks that had resulted in deterioration of some wood. The polyethylene film over the corrugated aluminum collector plate (Figure 1) had disintegrated and the collector was rebuilt without it, resulting in a single layer of glass over the aluminum. (Tybout and Löf (SHE) found that two glass plates are economically optimal everywhere except in the warmest of climates such as Miami or

Phoenix and most collectors that have been built use two). He reports only slightly lower efficiency than the first design with the film (44% as against 47%). This is comparable to the 45% efficiency reported by MIT House IV.

Mr Thomason believes that do-it-yourselfers can build their own solar houses. Plans and licenses are available for the "Thomason Solaris System" from Edmund Scientific Co., 150 Edscorp Bldg., Barrington, New Jersey 08007.

The following several pages describe the four houses. (SHAS)

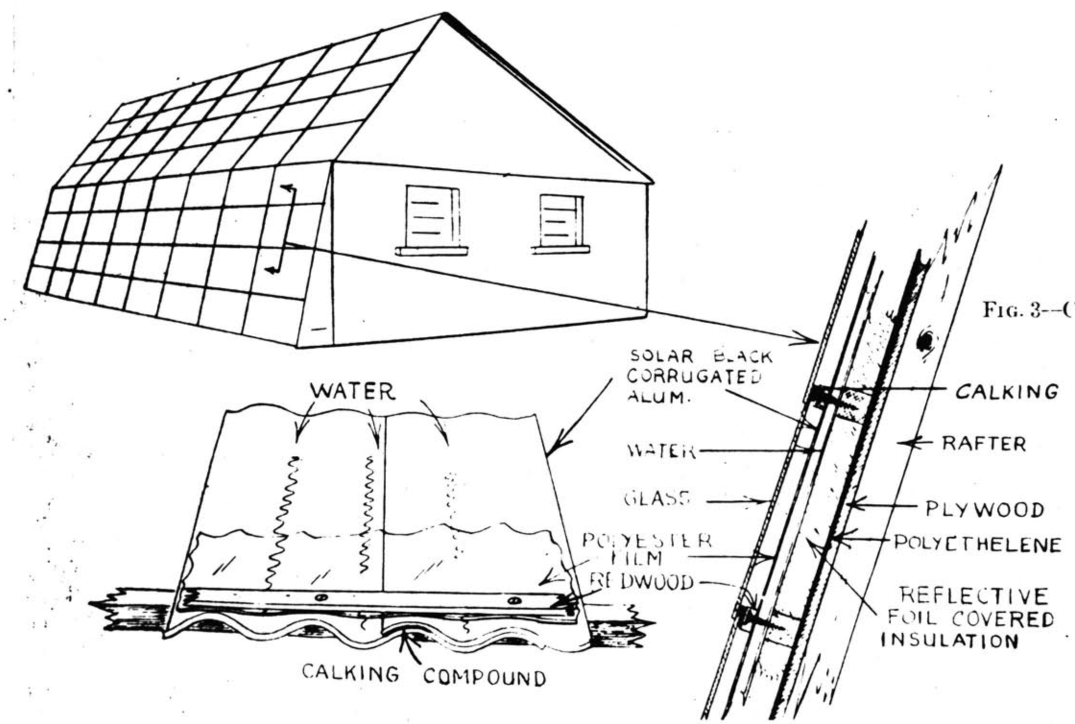


Fig. 3—Collector construction details.

HOUSE NUMBER 1

The relatively simple "Solaris Systems" for heating and cooling homes will now be explained in detail. The first house was designed as a solar house from the basement up. Overall, the house is 28 feet wide by 38 feet long. Total floor space is about 1500 square feet, about 900 being heated and air conditioned. Approximately one third of the lower level, an area 10 x 25 feet by 7 feet deep, is a heat storage bin. The remaining two thirds of the lower level is used for a basement, a recreation room, and a bomb shelter.

The heat bin was waterproofed, made airtight, and lined with three inches of insulation. Ordinary low-cost rough lumber was used to protect the insulation from being crushed by heat storage apparatus inside. Air distributing ductwork of concrete building blocks was constructed in the bottom of the bin. A steel tank 4 feet in diameter by 17 feet long, for 1600 gallons of water, was placed on top of the ductwork. Fifty tons, (3 truckloads) of fist-sized stones were poured around the tank.

A separate insulated compartment was constructed inside of the heat bin to heat the domestic water, both during the winter when the home was being heated and during the summer when the home was being air conditioned.

The top of the heat bin was formed by floor joists of the living quarters. Because warmed air from the heat bin rises, six inches of glass fiber insulation was placed between the joists. This minimized heat leakage up into the home from the bin when heat must be stored for cold days and kept the home from becoming overheated in spring and autumn when some days are warm and require little or no heat.

With this relatively simple low-cost heat storage apparatus large quantities of heat could be stored to keep the home warm for five or more reasonably cold, cloudy days in succession with no sunshine (temperatures of 25°-45° F).

The living quarters included 3 bedrooms, living room, bath, dinette-kitchen, and utility room. These areas, plus extensive closet space beneath the heat collector, were located entirely above ground and over the basement and heat bin area. The front of the house faced Walker Mill Rd., to the north. The front of the house, the front roof and the east and west ends were of conventional appearance. A solar heat collector was constructed to form the south side and south roof of the house.

The author departed from teachings of other solar energy researchers that a solar heat collector should face due south for optimum heat-collecting ability. His collectors were turned about 10 degrees west of south to take advantage of afternoon solar heat collecting conditions which are generally warmer and often clearer than mornings. Because of warmer afternoon air temperatures around the heat collector and in the attic behind the collector, less heat is lost and more is captured and transferred to the heat storage apparatus.

The solar heat collector was constructed in two sections. The top section was set at an angle of 45 degrees and extended from the peak of the roof down to ceiling level of the living quarters. This section was as long as the house, 38 feet, and measured 12 feet from top to bottom. The lower section was set at a steeper angle of 60 degrees and extended from the level of the ceiling down almost to the ground. This section was 38 feet long and 10 feet from top to bottom.

The base supports for the heat collector were the standard 2 x 6 roof rafters of the house. Plywood sheeting was nailed to these rafters as in usual building construction. A waterproof covering was placed over the plywood. Wood strips (2" x 3") were turned on edge and nailed through the plywood sheeting and waterproof covering to the rafters. Insulation bats 3 inches thick, with reflective aluminum foil coverings, were placed over the waterproof material and between the wood strips.

Corrugated aluminum sheets two feet wide were treated on one side with special materials to make them black to absorb solar heat. The sheets were installed with the corrugations, spaced 1-1/4 inches apart, extending from top to bottom. Polyester plastic film, 5 mils thick, was placed over the black corrugated aluminum and clamped into place by screws and redwood strips (3/4 x 1 inch). Ordinary window-glass panes were fastened to the redwood strips by screws and aluminum fasteners. This gave a spacing of 3/4 inch between the plastic film and the glass.

At the top of the heat collector 1/2-inch copper tubing was used as a distributor manifold. The tubing was drilled with hundreds of small holes, one hole over each valley in the black corrugated aluminum. At the bottom of the collector was an insulated gutter.

glass, 10¢; paint, screws, wood strips, water distributor and collector manifolds, 25¢; labor, 25¢.

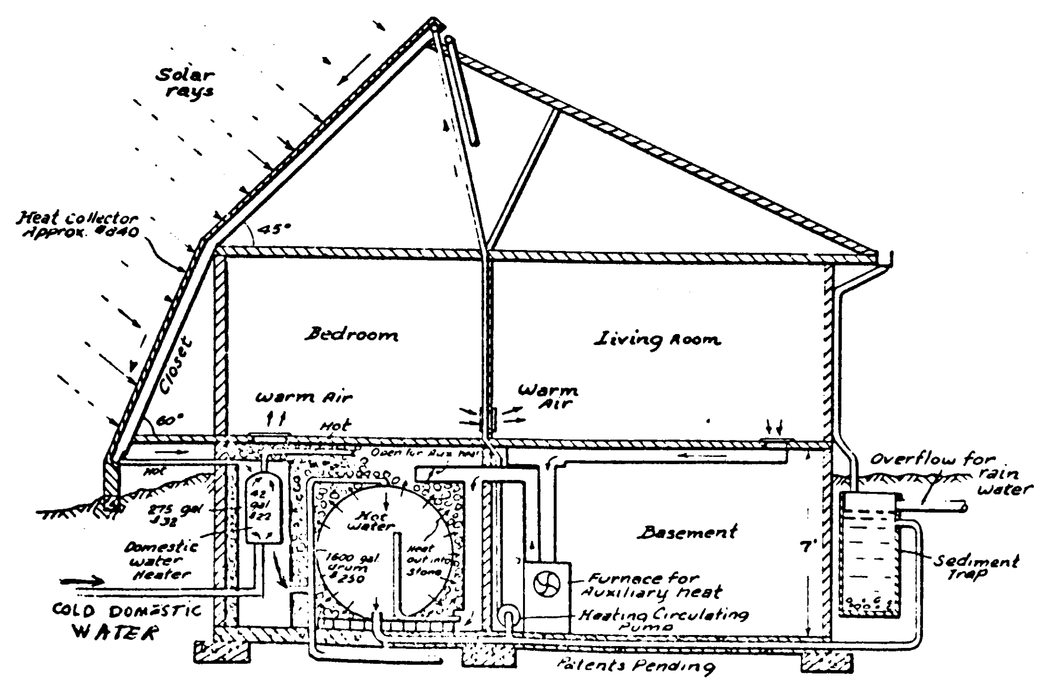
With this relatively simple apparatus large solar collectors were constructed at the very low cost of about a dollar per square foot. Collectors built by others had cost $3 to $5 per square foot.

Heating

Sun rays passing through the glass and plastic strike the black corrugated aluminum sheet and are converted to heat. Within a short time the black sheet becomes warmer than the water in the 1600-gallon steel tank in the heat storage bin. A small electric pump is automatically turned on to pump cold water from the bottom of the tank to the distributor manifold at the top of the collector. The water is warmed by the black corrugated sheet as it flows down the valleys from the top to the insulated gutter at the bottom. From the gutter the warm water flows to the heat bin where it passes through a heat exchanger and warms the domestic water. The warm water flows, from the heat exchanger into the top of the 1600-gallon tank. The water is recirculated through the solar heat collector until the water begins to be warmed, it in turn warms the 50 tons of stones around the tank; and this transfer of heat continues day and night. By the next morning the stones are warmed because the tank of water has given up much of its heat to the stones. The water is cool and ready to take on another load of heat when the sun shines again and turns on the recirculating pump.

An electric blower is turned on by a thermostat whenever the home gets cool. The blower draws cool air from the living quarters, filters it and blows it into the distributor ductwork of concrete building blocks in the bottom of the heat storage bin. These blocks are spaced apart slightly to let the air out into the warm stones and beneath the warm tank of water. The air is warmed as it moves by devious paths through the stones, and then is piped to the rooms of the home to warm them.

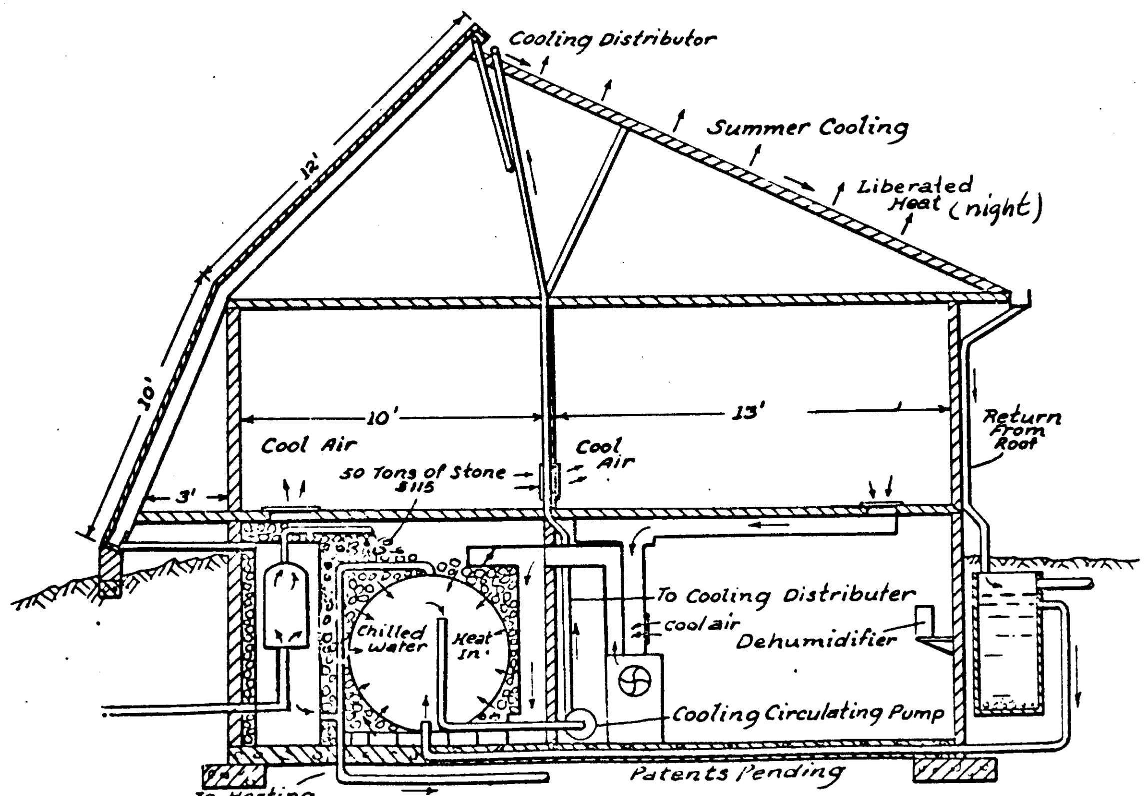
During periods of several sunny days the tank of water and surrounding stones will become increasingly warmer until enough heat is stored to keep the home warm for up to sever. cloudy, moderately cold days.



Winter Heating Cycle

mount of power. A 1/6-HP pump was used to carry water up to the north roof at night during the summer. The water was distributed by a perforated copper pipe at the crown of the roof to flow down over the no~th roof like rain. As it flowed it was chilled by evaporation, radiation to the sky, and contact with the cool night air. The cooled water, collected in the house roof gutter, was returned to the 1600-gallon tank where the cooled tank of water cooled the surrounding 50 tons of stones.

On hot days a thermostat turned on the blower to withdraw warm air from the home, filter it, rooftop cooler was as high as 25,000 B.T.U. per hour, roughly equivalent to two tons of cooling but using 1/6 HP instead of 2 HP as in conventional air conditioning units. However, when nights were calm with little wind, humid, cloudy, and warm, very little cooling of the water was possible. Then, the system had to draw on "coolness" stored from previous nights. For specific cooling data and further detailed information about this system see "Solar Space Heating and Air Conditioning in the Thomason Home," Harry E. Thomason, Solar Energy Journal, Vol. 4, No. 4, Oct., 1960, pages 1[illegible]-19.



Summer Cooling Cycle

House number 2

"Solar House No 2 was constructed in 1960, a year after No 1. The newer house was a 2 bedroom version having 1000 sq ft of floor space with approximately 675 being heated.... The solar heat collector on House No 2 has an area of 560 sq ft instead of 849 sq ft as in House No 1. However, No 2 has a 336 sq ft aluminum reflector extending out from the bottom of the solar heat collector. Additional solar heat is reflected up onto the collector to increase heat output by 15 to 30% .... instead of using rooftop cooling of the water for air conditioning, a simple 3/4 HP air-cooled compressor unit is used. The compressor operates at night to extract heat from the 1600-gallon tank of water and to discharge the heat through the condenser to night-time air. Thus, as compared with conventional air conditioning units, approximately twice as much cooling per hour is possible and only half as much electricity is used per Btu of cooling produced. This system was described in detail in the article, 'Solar-Heated House Uses 3/4 HP for Air Conditioning,' Harry E Thomason, ASHRAE Journal, Nov 1962, pp. 58-62." (SHAS - 13) but still yield valuable scientific and engineering data. The third house was designed to be more attractive, to incorporate many of the previously tested desirable features and to provide a testing ground for others. Some of its features can be revealed but others must be kept secret.

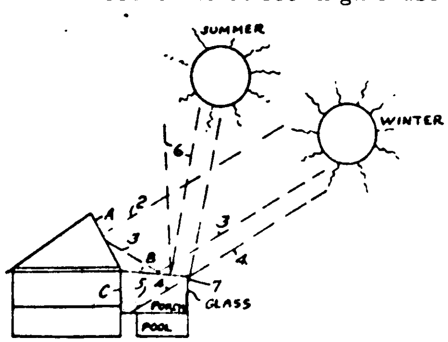
The third house is 74 feet long and 44 feet wide. It has seven heated rooms (4 bedrooms) and 2-1/2 baths. It has an enclosed solar-heated pool, sun porch, garage-workshop, laundry room, pump room and attic. It also has a recreation room, bowling alley and archery-rifle target range. Total usable floor space in the home is approximately 3,400 square feet, not including attic storage space. The seven rooms and two baths which are heated have about 1500 square feet of area.

A steep roof section over the attic supports the solar heat collector. Large collector panels are used, each being four feet wide by sixteen feet high. Corrugations, 2-1/2 inches apart, channel the water as it flows down from the top. Reflective foil and glass fiber insulation are used beneath the black corrugated heat collector sheet. Glass panes are encased in aluminum frames to cover the collector sheet.

The solar-heated pool and sunporch are located along the south side of the house and are covered by a slightly sloping roof section approximately 15 by 40 feet. A reflective aluminum roof is used so that much of the low wintertime sun will be reflected up onto the solar heat collector. This reflector is not visible from the ground, but functions similarly to the reflector used at Solar House No. 2. An open railing around the reflector-roof adds a touch of colonial styling, yet lets most of the sunlight in to the reflector and collector.

By keeping the solar heat collector and reflector up on the roof, landscape shrubbery and shade trees 30 to 50 feet high cause very little interference to incoming sunshine. Further details of this house are given in "A Solar House Completed -- Another Begun," Harry E. Thomason, Sun At Work (magazine). Fourth Quarter, 1963, pages 13-16.

The water from the swimming pool may be circulated through a portion of the solar heat collector and warmed. The heat output of 20% of the collector panels is sufficient to keep this indoor solar heated pool warm nine months of the year, whereas an unheated open pool can normally be used only about three months a year at this location on the outskirts of Washington, D.C. The pool is 11 x 25 feet, and 3 to 5 feet deep. Holding 6,000 to 7,000 gallons of water, it is completely lined with beautiful mosaic patterns of colorful ceramic tile. Obviously the pool enhances the value of the home, and the free solar-heating feature is an additional bonus.



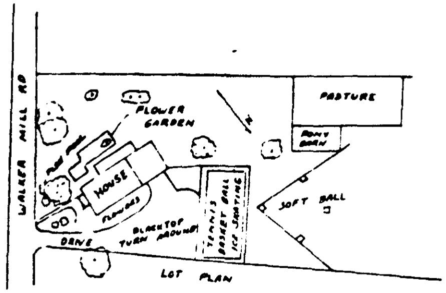
SOLAR HOUSE NO. 3 -- OPERATING PRINCIPLES

Winter

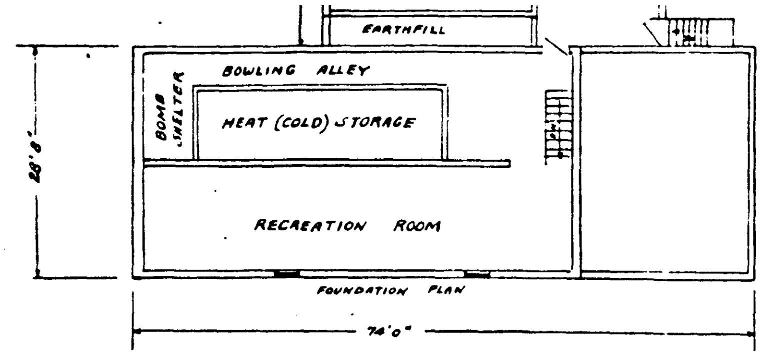
Sunrays at 2 strike collector A directly, rays 3 reflected onto collector by reflector roof B, rays 4 enter sunporch through glass to warm interior at 5 to "insulate" house wall C by low-temperature heat.

Summer

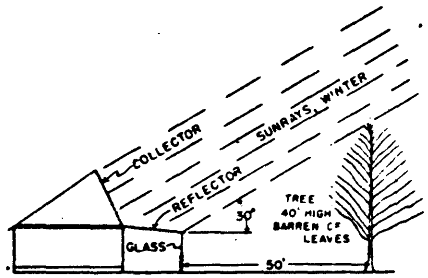
High-angle sunrays at 6 striking reflector B are "bounced" skyward while rays 7 do no enter windows, porch-pool area remain cooler.



(A) PLAN OF LOT

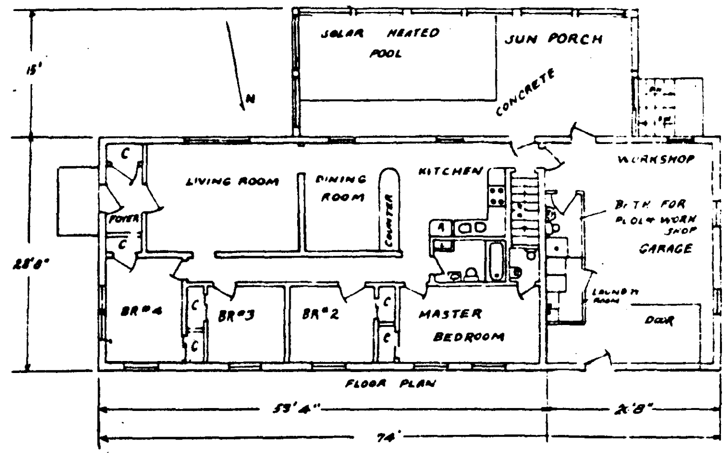


(C) FOUNDATION PLAN



(B) HOUSE IN RELATION TO TREES

Shade trees 35 to 40 feet high, only 50 feet away, have little adverse effect on the new solar house.



(D) FLOOR PLAN

HOUSE NUMBER 4

Solar House No. 4, built by Thomason Solar Homes Inc., is of inexpensive Swiss Chalet (A-frame) design. Low-cost "pancake" heat storage equipment was placed under the floor. (A shallow pond of water with Polyethylene liner and cover, and insulation below and above, formed the "pancake" design.) The heat collector was of very low-cost construction, utilizing black asphalt shingles as the solar heat collector sheet.

The low-cost solar heating system and the low-cost A-frame house design appear compatable for a low-cost cottage or secondary home. However, there are problems to be overcome. No pinehole free Polyethylene could be found for the pancake heat storage tank liner (other materials are more costly). Efficiency of the black asphalt shingles is a little lower than for black corrugated aluminum, and leakage is more apt to occur. More research and development will determine what features are worthwhile in

OTHER SOLAR HOUSES

In Mexico a fine large home was built with a small solar heating system. The volcanic pedregal was too hard to dig for a large heat storage bin, the heat collector was too small, and no insulation was used in the walls of the large home. Therefore, the solar heating system is too small to supply the major part of the heat load. In India a new system by Thomason is being tested for a flat roof building.

A firm in South Carolina planned to build Solar House No. 5 in 1965; but the project was abandoned since financing could not be obtained. In Warren, Vermont, University of Pennsylvania architectual students have begun the largest solar heated dwelling in the world: a condominium for five or more families. "Thomason Solaris System" will provide some solar heat; but, under the adverse conditions of cold, cloudy weather the percentage of solar heat is expected to be low. The total annual fuel saving could be

TABLE 4.6. Heating Season Climatic Data

Compiled from Records of the U. S. Weather Bureau and Other Sources

State	City	Average Temperature, Oct. 1–May 1	Lowest Temperature	Design Temperature Suggested by TAC	Average Wind Velocity, Dec., Jan., Feb., mph	Direction of Prevailing Wind, Dec., Jan., Feb.	Normal Degree Days, Total for Year
Ala.	Birmingham	53.9	−10	21	8.6	N	2618
Ariz.	Phoenix	59.5	16	31	3.9	E	1446
Ark.	Little Rock	51.6	−12	21	9.9	NW	3005
Calif.	Los Angeles	58.6	28	32	6.1	NE	1390
	San Francisco	54.3	27		7.5	N	3143
Colo.	Denver	39.3	−29	0	7.4	S	5863
D. C.	Washington	43.2	−15	14	7.3	NW	4598
Fla.	Jacksonville	61.9	10	31	8.2	NE	1161
Ga.	Atlanta	51.4	−8	22	11.8	NW	3002
Idaho	Lewiston	42.5	−13		4.7	E	4924
Ill.	Chicago	36.4	−23	−3	17	SW	6287
Ind.	Indianapolis	40.2	−25	2	11.8	S	5487
Iowa	Sioux City	32.1	−35		12.2	NW	6909
Kan.	Dodge City	40.2	−26		10.4	NW	5077
Ky.	Louisville	45.2	−20	9	9.3	SW	4428
La.	New Orleans	61.5	7	36	9.6	N	1208
Mass.	Boston	37.6	−18	8	11.7	W	5943
Mich.	Detroit	35.4	−24	4	13.1	SW	6580
Minn.	Minneapolis	29.6	−33	−15	11.5	NW	7989
Mo.	St. Louis	43.3	−22	3	11.8	NW	4610
Mont.	Billings	34.7	−49	−17	12.4	W	7119
Neb.	Lincoln	37.0	−29	−2	10.9	N	6010
N. M.	Santa Fe	38.0	−13		7.3	NE	6124
N. Y.	Buffalo	34.7	−21	3	17.7	W	6935
	New York	40.3	−14		13.3	NW	5306
N. C.	Raleigh	49.7	−2	20	7.3	SW	3281
N. D.	Bismarck	24.5	−45	−21	9.1	NW	8969
Ohio	Cleveland	36.9	−18	6	14.5	SW	6171
Okla.	Oklahoma City	48.0	−17	14	12.0	N	3698
Oreg.	Portland	45.9	−2	22	6.5	S	4379
Pa.	Philadelphia	41.9	−11		11.0	NW	4749
S. C.	Charleston	56.9	7	26	11.0	N	1870
Tenn.	Knoxville	47.0	−16		6.5	SW	3665
Tex.	El Paso	53.0	−2		10.5	NW	2538
	San Antonio	60.7	4	32	8.2	N	1424
Utah	Salt Lake City	40.0	−20	7	4.9	SE	5637
Va.	Lynchburg	45.2	−7		5.2	NW	4082
Wash.	Seattle	45.3	3	24	9.1	SE	4864
Wis.	Milwaukee	33.0	−25	−6	11.7	W	7086
Wyo.	Cheyenne	33.9	−38	−3	13.3	NW	7549

APPENDIX III

TABLE 4.1. Conductivities k, Conductances C, and Resistances R of Building and Insulating Materials—Design Values[a]

These constants are expressed in Btuh per sq ft per deg F temperature difference. Conductivities k are per inch thickness and conductances C are for thickness or construction stated, not per inch thickness.

Material	Description			Density, (lb per cu ft)	k	C	R Per Inch Thickness $\left(\frac{1}{k}\right)$	R For Thickness Listed $\left(\frac{1}{C}\right)$
Air spaces[b]	Position	Heat Flow	Thickness					
	Horizontal	Up	¾–4 in.	—	—	1.18	—	0.85
	Sloping (45°)	Up	¾–4 in.	—	—	1.11	—	0.90
	Vertical	Horizontal	¾–4 in.	—	—	1.03	—	0.97
	Sloping (45°)	Down	¾–4 in.	—	—	0.97	—	1.03
	Horizontal	Down	¾ in.	—	—	0.98	—	1.02
	Horizontal	Down	8 in.	—	—	0.80	—	1.25
Air surfaces[c]	Position		Heat Flow					
Still air	Horizontal		Up	—	—	1.63	—	0.61
	Up Sloping (45°)		Up	—	—	1.60	—	0.62
	Vertical		Horizontal	—	—	1.46	—	0.68
	Sloping (45°)		Down	—	—	1.32	—	0.76
	Horizontal		Down	—	—	1.08	—	0.92
15-mph wind	Any position—any direction			—	—	6.00	—	0.17
7½-mph wind	Any position—any direction			—	—	4.00	—	0.25
Building board[d]								
Boards,	Gypsum or plasterboard		⅜ in.	50	—	3.10	—	0.32
panels,	Gypsum or plasterboard		½ in.	50	—	2.25	—	0.45
sheathing, etc.	Plywood			34	0.80	—	1.25	—
Building paper	Vapor—permeable felt			—	—	16.70	—	0.06
	Vapor—seal, 2 layers of mopped 15-lb felt			—	—	8.35	—	0.12
	Vapor—seal, plastic film			—	—	—	—	Negl
Flooring Materials	Asphalt tile		⅛ in.	120	—	24.80	—	0.04
	Ceramic tile		1 in.	—	—	12.50	—	0.08
	Cork tile		⅛ in.	—	—	3.60	—	0.28
	Plywood subfloor		⅝ in.	—	—	1.28	—	0.78
	Rubber or plastic tile		⅛ in.	110	—	42.40	—	0.02
	Terrazzo		1 in.	—	—	12.50	—	0.08
	Wood subfloor		25/32 in.	—	—	1.02	—	0.98
	Wood, hardwood finish		¾ in.	—	—	1.47	—	0.68
Insulating Materials	Cotton fibers			0.8–2.0	0.26	—	3.85	—
Blanket and batt	Mineral wool, fibrous form, processed from rock, slag, or glass[e]			1.5–4.0	0.27	—	3.70	—
	Wood fiber[e]			3.2–3.6	0.25	—	4.00	—
Board	Glass fiber			9.5	0.25	—	4.00	—
	Acoustical tile[f]		½ in.	—	—	0.84	—	1.19
	Sheathing (impreg. or coated)			20.0	0.38	—	2.63	—
Board and slabs	Cellular glass			9.0	0.40	—	2.50	—
	Plastic (foamed)			1.62	0.29	—	3.45	—
Loose fill	Mineral wool (glass, slag, or rock)			2.0–5.0	0.30	—	3.33	—
	Vermiculite (expanded)			7.0	0.48	—	2.08	—
Roof insulation	All types[g]							
	Preformed, for use above deck							
	Approx.		1 in.	—	—	0.36	—	2.78
	Approx.		2 in.	—	—	0.19	—	5.26
	Approx.		3 in.	—	—	0.12	—	8.33
Masonry Materials	Cement mortar			116	5.00	—	0.20	—
Concretes	Lightweight aggregates, including expanded shale, clay, or slate; expanded slags; cinders; pumice; perlite; vermiculite; also cellular concretes			120	5.2	—	0.19	—
				80	2.5	—	0.40	—
				40	1.15	—	0.86	—
				20	0.70	—	1.43	—
	Sand and gravel or stone aggregate (not oven dried)			140	12.00	—	0.08	—

TABLE 4.1 (Continued)

Material	Description		Density, (lb per cu ft)	k	C	R Per Inch Thickness $\left(\frac{1}{k}\right)$	R For Thickness Listed $\left(\frac{1}{C}\right)$
Masonry Units	Brick, common		120	5.00	—	0.20	—
	Brick, face		130	9.00	—	0.11	—
	Clay tile, hollow						
	1 cell deep	4 in.	—	—	0.90	—	1.11
	2 cells deep	8 in.	—	—	0.54	—	1.85
	3 cells deep	12 in.	—	—	0.40	—	2.50
	Concrete blocks, three oval core						
	Sand & gravel aggregate	4 in.	—	—	1.40	—	0.71
		8 in.	—	—	0.90	—	1.11
		12 in.	—	—	0.78	—	1.28
	Cinder aggregate	4 in.	—	—	0.90	—	1.11
		8 in.	—	—	0.58	—	1.72
		12 in.	—	—	0.53	—	1.89
	Gypsum partition tile:						
	3 × 12 × 30 in. 4-cell		—	—	0.74	—	1.35
	4 × 12 × 30 in. 3-cell		—	—	0.60	—	1.67
Plastering Materials	Cement plaster, sand aggregate		116	5.00	—	0.20	—
	Gypsum plaster:						
	Sand aggregate		105	5.60	—	0.18	—
	Sand aggregate on metal lath ¾ in.		—	—	7.70	—	0.13
	Lightweight aggregate		45	1.50	—	0.67	—
	Lightweight agg. on metal lath ¾ in.		—	—	2.13	—	0.47
Roofing	Asphalt roll roofing		70	—	6.50	—	0.15
	Asphalt shingles		70	—	2.27	—	0.44
	Built-up roofing	⅜ in.	70	—	3.00	—	0.33
	Sheet metal		—	400+	—	Negl	
	Wood shingles		—	—	1.06	—	0.94
Siding Materials (On flat surface)	Shingles						
	Wood, 16-in. 7½-in. exposure		—	—	1.15	—	0.87
	Siding						
	Wood, drop, 1 × 8 in.		—	—	1.27	—	0.79
	Wood, bevel, ½ × 8 in., lapped		—	—	1.23	—	0.81
	Wood, bevel, ¾ × 10 in., lapped		—	—	0.95	—	1.05
	Wood, plywood, ⅜ in., lapped		—	—	1.59	—	0.59
Woods	Maple, oak, and similar hardwoods		45	1.10	—	0.91	—
	Fir, pine, and similar softwoods		32	0.80	—	1.25	—

[a] Representative values for dry materials at 75 F mean temperature, selected by the ASHAE Technical Advisory Committee on Insulation. They are intended as design (not specification) values for materials of building construction in normal use. For conductivity of a particular product, the user may obtain the value supplied by the manufacturer or secure the results of unbiased tests.

[b] Air-space resistance values shown here are based on a temperature difference of 20 F and a mean temperature of 50 F for spaces faced both sides with ordinary *nonreflective* materials.

[c] Surface resistance values shown here are for ordinary *nonreflective* materials.

[d] See also Insulating Materials, Board.

[e] Includes paper backing and facing if any.

[f] Insulating values of acoustical tile vary depending on density of the board and on the type, size, and depth of the perforations.

[g] The U. S. Department of Commerce "Simplified Practice Recommendation for Thermal Conductance Factors for Preformed Above-Deck Roof Insulation," No. R 257-55, recognizes the specification of roof insulation on the basis of the C values shown. Roof insulation is made in thicknesses to meet these values. Therefore, thickness supplied by different manufacturers may vary depending on the k value of the particular material.

Table 3.4. Solar Absorptance (1.0-Albedo) and Long-wave Emittance of Various Surfaces (IUSE-51)

Material	Solar absorptance (0.3 to 2.5 microns)	Long-wave emittance, ε (2.5 microns up)
"Hohlraum," theoretical perfectly blackbody	1.00	0.99 +
Magnesium carbonate, $MgCO_3$ (white reference, solid)	0.04	0.79†
Water (1.0—single surface reflectance, $i = 60°$)	0.94	0.95–0.96
Ice, with sparse snow cover; sheet	0.31	0.96–0.97
Snow, ice granules (approximate 1/32-in. diameter)	0.33 calc.	0.89
Snow, fine particles like frost; fresh, brightest	0.13	0.82
Frozen soil	—	0.93–0.94
Sand, dry playa; Monterey powdered	0.45†	0.84‡
Desert surface	0.75	approx. 0.90
Sand, dry	0.82	
Sand, wet	0.91	approx. 0.95
Moist ground, 70–95 per cent bare	0.88–0.91	
Ground, dry plowed	0.75–0.80	approx. 0.9
Grass, high, dry	0.67–0.69	
Common vegetable fields and shrubs	0.72–0.76	
Common vegetable fields and shrubs, wilted	0.70	
Oak leaves (1.0—reflectance, at 0.6 and 3 microns)	0.71–0.78	0.91–0.95
Alfalfa, dark green	0.97†	(0.95)
Oak woodland	0.82	approx. 0.9
Pine forest	0.86	
Paper, white	0.25–0.28	0.95
Plaster, white	0.07	0.91
Bricks, red	0.55	0.92
Concrete	0.60	0.88
Asbestos slate	0.81	0.96
Linoleum, red-brown	0.84	0.92
Wood, planed oak	—	0.90
Glass pane* (solar = 1.0–2 reflections, $i = 35°$)	0.90	0.94
White paint (0.017 in. on aluminum)	0.20	0.91
Black paint (0.017 in. on aluminum)	0.94–0.98	0.88
Aluminum paint, bright, new	0.20	0.43
Aluminum foil	0.15	0.01–0.05
Aluminum combination finish (at 0.6 micron); new	0.32	0.10‡
Galvanized iron, clean, new	0.65	0.13‡
Galvanized sheet iron, gray oxidized	(0.8)	0.28

* Absorption of solar energy in double-strength pane is approximately 4 per cent.
† Calculated from spectral reflectance, assuming Moon's standard solar-energy spectrum for airpath = 2.0.
‡ Calculated from spectral reflectance, assuming that the 15-m determination applies at all longer wavelengths.

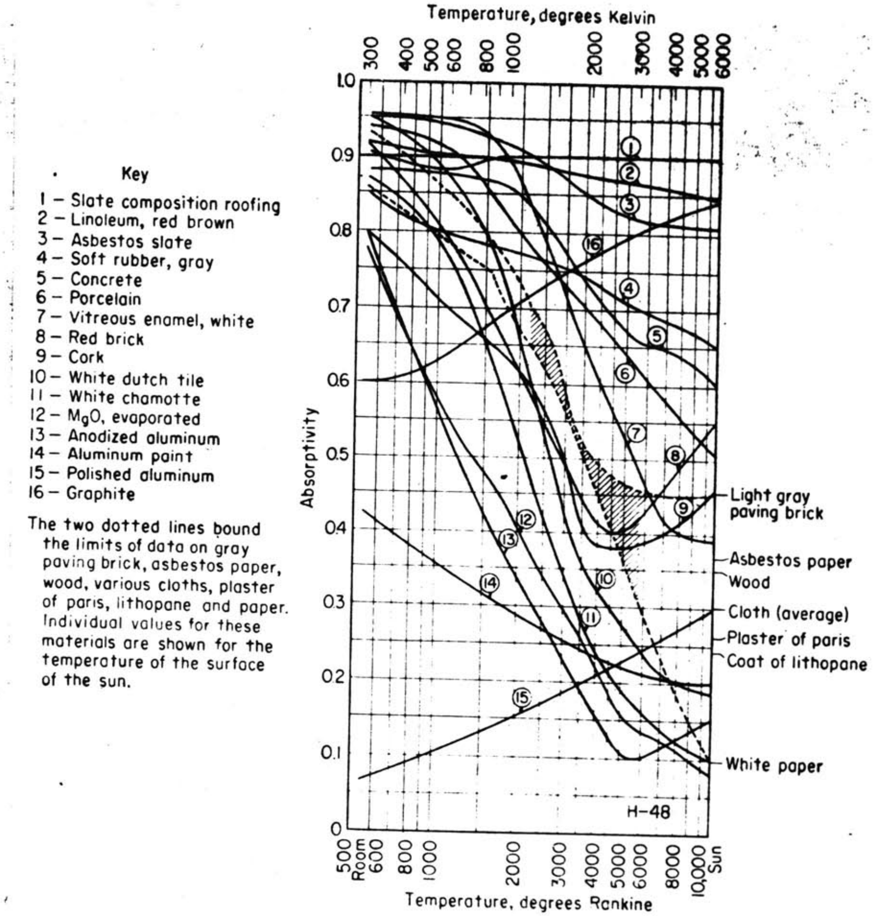


Fig 1.2. Absorptivities of various materials for radiation originating at temperatures ranging from approximately room temperature to the temperature of the sun. (IUSE-61)

Energy or Work Equivalents

Joules	Kilogram-meters	Foot-pounds	Kilo-watt-hours	Metric horse-power-hours	Horse-power-hours	Liter-atmospheres	Kilo-calories	British thermal units
1	0.10197 $\bar{1}.00848$	0.7376 $\bar{1}.86780$	$0.0_{6}2778$ $\bar{7}.44370$	$0.0_{6}3777$ $\bar{7}.57711$	$0.0_{6}3725$ $\bar{7}.57113$	0.009869 $\bar{3}.99427$	$0.0_{3}2388$ $\bar{4}.37800$	$0.0_{3}9478$ $\bar{4}.97670$
9.80665 0.9915207	1	7.233 0.85932	$0.0_{5}2724$ $\bar{6}.43521$	$0.0_{5}37037$ $\bar{6}.56863$	$0.0_{5}3653$ $\bar{6}.56265$	0.09678 $\bar{2}.98579$	0.002342 $\bar{3}.36961$	0.009295 $\bar{3}.96825$
1.356 0.13220	0.1383 $\bar{1}.14068$	1	$0.0_{6}3766$ $\bar{7}.57590$	$0.0_{6}51206$ $\bar{7}.70932$	$0.0_{6}50505$ $\bar{7}.70333$	0.01338 $\bar{2}.12647$	$0.0_{3}3238$ $\bar{4}.51029$	0.001285 $\bar{3}.10890$
3.600×10^{6} 6.55630	3.671×10^{5} 5.56478	2.655×10^{6} 6.42410	1	1.3596 0.13342	1.341 0.12743	35528 4.55057	859.9 2.93443	3412 3.53303
2.648×10^{6} 6.42288	270000 5.43136	1.9529×10^{6} 6.29068	0.7355 $\bar{1}.86658$	1	0.9863 $\bar{1}.99401$	26131 4.41715	632.4 2.80098	2510 3.39961
2.6845×10^{6} 6.42887	2.7375×10^{5} 5.43735	1.98×10^{6} 6.29667	0.7457 $\bar{1}.87356$	1.0139 0.00598	1	26493 4.42314	641.2 2.80699	2544 3.40557
101.33 2.00573	10.333 1.01421	74.74 1.87353	$0.0_{4}2815$ $\bar{5}.44952$	$0.0_{4}3827$ $\bar{5}.58284$	$0.0_{4}3775$ $\bar{5}.57686$	1	0.02420 $\bar{2}.38382$	0.09604 $\bar{2}.98246$
4187 3.62191	426.9 2.63036	3088 3.48971	0.001163 $\bar{3}.06558$	0.001581 $\bar{3}.19902$	0.001560 $\bar{3}.19304$	41.32 1.61618	1	3.968 0.59861
1055 3.02300	107.6 2.03178	778.2 2.89110	$0.0_{3}2931$ $\bar{4}.46697$	$0.0_{3}3985$ $\bar{4}.60042$	$0.0_{3}3930$ $\bar{4}.59444$	10.41 1.01757	0.25200 $\bar{1}.40139$	1

Conversion of Energy, Work, Heat *

	Ft-lb to kilo-gram-meters	Kilo-gram-meters to ft-lb	Ft-lb to Btu	Btu to ft-lb	Kilo-gram-meters to kilo-calories	Kilo-calories to kilo-gram-meters	Joules to calories	Calories to joules
1	0.1383	7.233	0.001285	778.2	0.002342	426.9	0.2388	4.187
2	0.2765	14.47	0.002570	1,556.	0.004685	853.9	0.4777	8.374
3	0.4148	21.70	0.003855	2,334.	0.007027	1,281.	0.7165	12.56
4	0.5530	28.93	0.005140	3,113.	0.009369	1,708.	0.9554	16.75
5	0.6913	36.16	0.006425	3,891.	0.01172	2,135.	1.194	20.93
6	0.8295	43.40	0.007710	4,669.	0.01405	2,562.	1.433	25.12
7	0.9678	50.63	0.008995	5,447.	0.01640	2,989.	1.672	29.31
8	1.106	57.86	0.01028	6,225.	0.01874	3,415.	1.911	33.49
9	1.244	65.10	0.01156	7,003.	0.02108	3,842.	2.150	37.68

* EXAMPLE: 1 ft-lb = 0.1383 kg-m.

Thermal Conductivity

Calories per sec per sq cm per cm per deg C	Watts per sq cm per cm per deg C	Calories per hr per sq cm per cm per deg C	Btu per hr per sq ft per ft per deg F	Btu per day per sq ft per in. per deg F
1	4.187	3,600	241.9	69,670
0.2388	1	860	57.79	16,641
0.0002778	0.001163	1	0.0672	19.35
0.004134	0.01731	14.88	1	288
0.00001435	0.00006009	0.05167	0.00347	1

Thermal Conductance

Calories per sec per sq cm per deg C	Watts per sq cm per deg C	Calories per hr per sq cm per deg C	Btu per hr per sq ft per deg F	Btu per day per sq ft per deg F
1	4.187	3,600	7,373	176,962
0.2388	1	860	1,761	42,267
0.0002778	0.001163	1	2.048	49.16
0.0001356	0.0005678	0.4882	1	24
0.000005651	0.00002366	0.02034	0.04167	1

Heat Flow

Calories per sec per sq cm	Watts per sq cm	Calories per hr per sq cm	Btu per hr per sq ft	Btu per day per sq ft
1	4.187	3,600	13,272	318,531
0.2388	1	860	3,170	76,081
0.0002778	0.001163	1	3.687	88.48
0.00007535	0.0003154	0.2712	1	24
0.000003139	0.00001314	0.01130	0.04167	1

(SHF - 83,84)

APPENDIX VI

(IUSE - 245)

(SHE - 291)

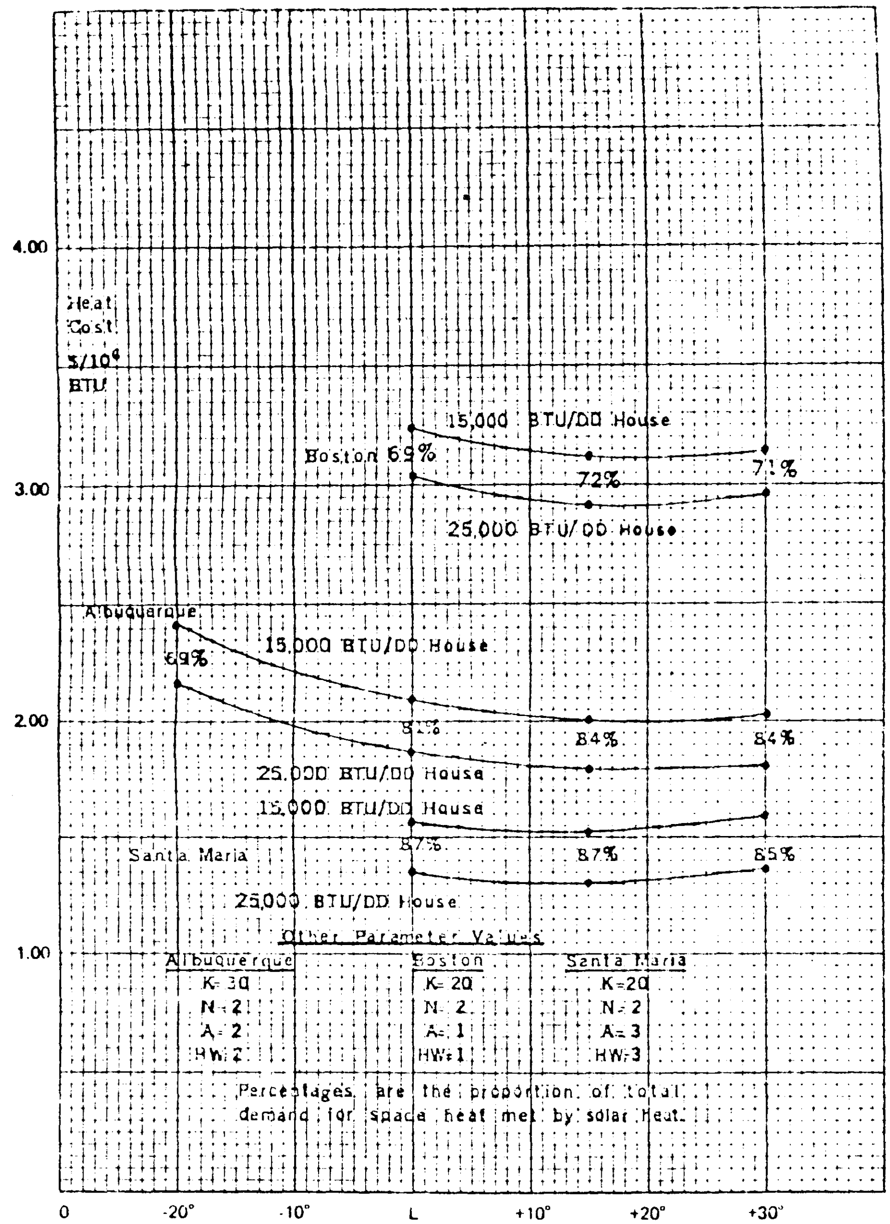


Figure 7
Influence of Collector Tilt

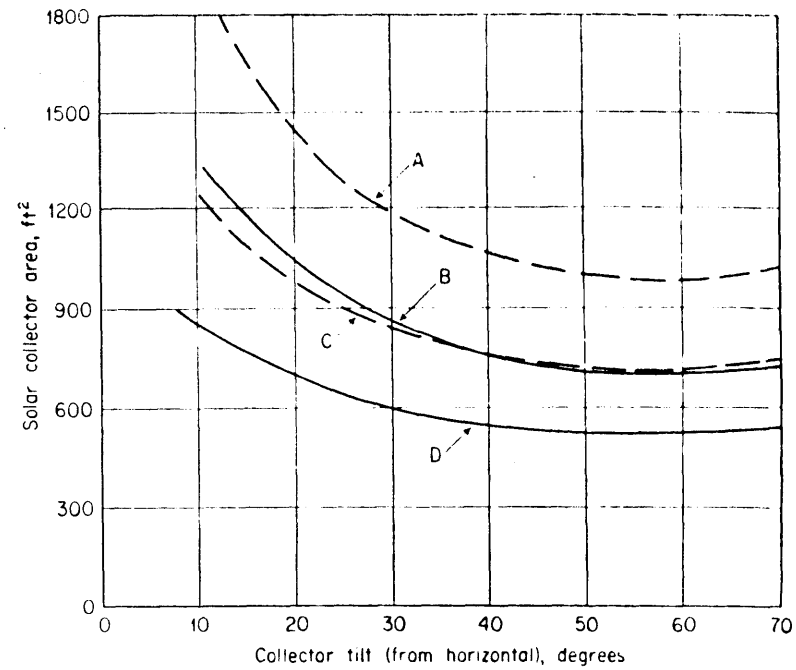


Fig. 11.1. Effect of tilt and type of glass on collector-area requirement. Computations based on normal solar and temperature data at Denver, Colo., latitude 40° for building having heat requirement of 22,500 Btu/degree day, equivalent to 61,000 Btu/hr at zero degrees outside temperature. Heat storage assumed adequate to smooth fluctuations within each month; performance based on overlapped-plate collector with single covers, four sections in series, operated at air rate of 1.5 ft³/min per square foot of collector.

Curve A Ordinary glass collector, 4/5 of 6000 deg.-day annual load carried by solar system.

Curve B Low reflectivity glass collector, 4/5 of 6000 deg.-day annual load carried by solar system.

Curve C Ordinary glass collector, 2/3 of 6000 deg.-day annual load carried by solar system.

Curve D Low-reflectivity glass collector, 2/3 of 6000 deg.-day annual load carried by solar system.