FINAL REPORT

NASA Grant NGR-11-002-166

COMPARATIVE EVALUATION OF SOLAR, FISSION,
FUSION, AND FOSSIL ENERGY RESOURCES

PART I

SOLAR ENERGY

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(NASA-CR-137242) COMPARATIVE EVALUATION OF SOLAR, FISSION, FUSION, AND FOSSIL ENERGY RESOURCES. PART 1: SOLAR ENERGY Final Report (Georgia Inst. of Tech.) N74-18721
CSCL 10A G3/03 Unclas 16609

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SOLAR ENERGY: ITS TIME HAS COME

In 1970 the total energy consumed in the United States was about 65×10^{15} Btu[1], which is equal to the energy of sunlight received by 4300 square miles of land, or only 0.15% of the land area of the continental U.S. Thus, even if this energy were utilized with an efficiency of only 10%, the total energy needs of the U.S. could be supplied by solar collectors covering only 1.5% of the land area, and this energy would be supplied without any environmental pollution. With the same 10% utilization efficiency, about 4% of the land area would supply all the energy needs in the year 2000. By comparison, at present 15% of the U.S. land area is used for growing farm crops.[2] For some applications, such as heating water and space heating for buildings, the utilization efficiency can be much greater than 10%, and the collectors located on vertical walls and rooftops of buildings, so the 4% estimate represents an upper limit and actual land area requirements may be considerably smaller.

As a practical matter, even though sunlight can provide all our energy needs without pollution, in the forseeable future solar energy will not provide all or even most of this energy. Over the past century fossil fuels have provided most of our energy because energy from fossil fuels has usually been cheaper and more convenient than energy from available alternative energy sources, and until recently environmental pollution has been of little concern. The construction of large nuclear electric generating plants is presently underway, and nuclear power will play an increasingly important role ; so in the coming decades a variety of energy sources will supply the U.S. energy needs, and solar energy will only be utilized when it is competitive with alternative energy sources.

Over the past few years, energy forecasts[3-12] have been made which predict large increases in the consumption of oil and coal as well as a rapid increase in nuclear generation. However, these forecasts predict that the domestic production of oil would not be sufficient to keep pace with demand, so large increases in oil imports would be necessary. The recent oil embargo and rapid escalation of the cost of foreign crude oil has cast doubt on the ability of the U.S. to supplement its energy needs from foreign imports, so the President has urged that the U.S. become self sufficient in its energy supplies by 1980. This will require rapidly developing additional domestic energy resources. Solar energy, which so far has seen insignificant use in the U.S., can be rapidly utilized to make a significant impact as a new energy resource over the next few years. The most immediate large-scale applications would be the heating and cooling of buildings, heating water, and supplying heat for industrial and agricultural drying operations. Over the longer term, solar energy can also be used for pollutionless electric power generation.

The NSF/NASA Solar Energy Panel[13] identified three broad applications as "most promising from technical, economic, and energy quantity standpoints. These are: (1) the heating and cooling of residential and commercial buildings, (2) the chemical and biological conversion of organic materials to liquid, solid, and gaseous fuels, and (3) the generation of electricity". It also reported that "solar energy can be developed to meet sizable portions of the Nation's future energy needs". Energy for space heating, air conditioning and water heating for buildings presently accounts for about 22% of the total energy consumption in the U.S.[14], and virtually all this energy is supplied by the combustion of high quality fossil fuels. Solar heat could provide about half this energy, and supply it more economically[15].

AVAILABILITY OF SOLAR ENERGY

In order to evaluate the economics and performance of systems for the utilization of solar energy in a particular location, a knowledge of the available solar radiation at that place is essential. Thus, the utilization of solar energy, as with any other natural resource, requires detailed information on availability.

For approximate calculations, average values of energy availability are often used. Cherry[16] discusses solar energy availability as follows: "Availability of Solar Energy: Solar energy arrives on the surface of the U.S. at an average rate of 1500 BTU/ft^2/day (about 42 x 10^9 BTU/mi^2/day). Over the period of a year a square mile receives about 15 x 10^{12} BTU. In 1970 the total energy consumed by the U.S. for all purposes was about 65 x 10^{15} BTU.[1] Thus 4300 sq. mi. of continental U.S. land receives on the average in one year the equivalent of all the U.S. energy needs! At 10% conversion efficiency 43,000 sq. mi. - about 1.5% of the land area of the 48 contiguous states - could produce the amount of power the U.S. consumed in 1970". Boer[17] describes solar energy availability as "a double periodic function with a 24 h and a 365 d period length, superimposed with a fluctuating screening function (cloud cover). The maximum amplitude of this function is approximately 1 KW/m^2 and for the continental U.S.A., it integrates to an average energy influx of approximately 1800 KWh/m^2 year". As a rule-of-thumb, the yearly average solar energy received in the United States is about 60 BTU/ft^2 hr.

However, precise evaluation of proposed solar energy systems requires accurate data on the solar intensity, spectrum, incident angle, and cloudiness as a function of time, at the place where the solar energy system is to be located. Past surveys of worldwide solar radiation (insolation) have been based on very limited data for most areas. A large amount of data is available in the United States and Japan on the time dependent direct and diffuse intensity function. Many solar applications require data on the probability of cloudy periods of specific duration, and this type of data is seldom available. Also, in some cases the results of radiation surveys are reported on an annual basis only, which precludes the use of this information for the rational design of solar energy systems in most areas where seasonal variations of radiation are large.

Lof[18] conducted a survey of world solar radiation and compiled data from many sources . He described several types of solar radiation data, including "direct radiation at normal incidence, direct plus diffuse radiation at normal incidence, direct radiation on a horizontal surface, direct plus diffuse radiation on a horizontal surface, and each of these on tilted and on vertical surfaces. For each type of measurement, there are also the possible choices of maximum and minimum values in selected periods of time. Finally, it is necessary to decide on what sort of averaging should be employed; seasonal, monthly, daily, or hourly. For devices employing focusing systems, normal incidence of direct radiation would of course be preferred. For flat-plate systems, it would be preferable to have total (direct plus diffuse) radiation on a sloping surface if the collector is to be used in that position. Some design purposes would best be served by use of maximum radiation values; whereas, performance over a period of time might be determined most readily by an appropriate mean radiation figure and a distribution parameter. No single type of data or method of compiling will serve all needs.

The form of the data most available and most frequently reported is total radiation (direct plus diffuse) on a horizontal surface received each day or in some cases each hour. This is, moreover, probably the most generally useful form of radiation data, as methods are available for estimating other types from these figures". The types of instruments used to measure this data are also described.

"Solar radiation is measured by several different types of instruments having various characteristics and degrees of accuracy. With few exceptions, radiation-measuring instruments in use are of two main types: the thermoelectric type and the bimetallic expansion type. Each of these has variations. The thermoelectric types include the Kimball pyranometer (manufactured by Eppley) and the Moll-Gorczynski pyranometer (manufactured by Kipp and Zonen). A difference in temperature of black and white surfaces in a glass-enclosed chamber is caused by solar-radiation absorption; the electric output from thermopiles in these units is usually recorded on some type of chart or totalled by means of an integrator. If well calibrated and maintained, these instruments can provide daily totals of solar and sky radiation usually within three percent of true values; most recorded data are probably less accurate.

The principal radiation meter of the bimetallic expansion type is the Fuess-Robitzsch pyranometer or pyranograph (with self-contained recorder). In this instrument, differential expansion of a metallic element due to solar absorption causes the movement of a stylus on a clock-driven chart. Its accuracy is lower than the thermoelectric types, deviations of ten percent from true value not being uncommon. Another meter of this type is the Michelson pyranometer.

Unless a pyranometer is provided with some type of integrator, the common method for obtaining hourly and daily total radiation values is by planimetry from the chart records.

Another radiation instrument used by a few stations is the Bellani pyranometer, which provides an indication of total solar radiation by the quantity of a liquid that has distilled from a solar-heated evaporating chamber. Periodic measurement of the distilled liquid permits estimation of the incident radiation during the interval.

In the United States, the Eppley pyranometer is most frequently used, whereas in Europe and Africa, the Kipp is more common. The Robitzsch bimetallic type is simpler and cheaper, and fairly widely used in South America and Asia, as well as in scattered stations elsewhere in the world.

The other type of data used in this study is the percentage of possible sunshine or the hours of sunshine per day as measured by the Campbell-Stokes sunshine recorder. This instrument employs a spherical lens to focus direct sunshine onto a paper chart. Discoloration of the chart occurs, due to heat, whenever the solar disc can be seen. The length of the discolored line divided by the total length of the chart corresponding to the time between sunrise and sunset is the percent possible sunshine for the day. This instrument is widely used and is actually a standard for this type of measurement."

Regular measurements of sunshine duration and cloudiness are made at numerous weather stations throughout the world, and these records usually cover periods of 20 to 60 years or more. The average daily radiation is a function of sunshine duration at the particular location, and is correlated with the amount received outside the atmosphere Q_o by

$$Q = Q_o \left(a + b \frac{S}{S_o}\right)$$

where Q is the average daily radiation received at the surface location, S is the number of hours of sunshine recorded at the site per day, and S_o is the maximum number of hours of sunshine that are possible at the site per day (unobstructed horizon), and a and b are constants. This relationship is based on work by Angstrom.[19] Lof[18] gives values of a, b and S/S_o as follows:

TABLE 1 - CLIMATIC CONSTANTS

Location	S/S_o	a	b
Charleston, S.C.	0.67	0.48	0.09
Atlanta, Ga	0.59	0.38	0.26
Miami, Fla.	0.65	0.42	0.22
Madison, Wis.	0.58	0.30	0.34
El Paso, Tex.	0.84	0.54	0.20
Poona, India (Monsoon)	0.37	0.30	0.51
(Dry)	0.81	0.41	0.34
Albuquerque, N.M.	0.78	0.41	0.37
Malange, Angola	0.58	0.34	0.34
Hamburg, Germany	0.36	0.22	0.57
Ely, Nevada	0.77	0.54	0.18
Brownsville, Tex.	0.62	0.35	0.31
Tamanrasset, Sahara	0.83	0.30	0.43
Honolulu, Hawaii	0.65	0.14	0.73
Blue Hill, Mass	0.52	0.22	0.50
Buenos Aires, Arg.	0.59	0.26	0.50
Nice, France	0.61	0.17	0.63
Darien, Manchuria	0.67	0.36	0.23
Stanleyville, Congo	0.48	0.28	0.39

The present status of solar energy availability measurements was described at the recent NSF/NOAA Solar Energy Data Workshop[20]. Ed Jessup (from NOAA) described the National Weather Service solar radiation network which has over 90 measuring sites. A few of these are "EPPLEY

Model II" sites which have twice the accuracy of the other sites. Three basic problems of many sites are equipment deterioration, inadequate monitoring and "program disorganization". These problems are being rectified. Data is stored at one minute intervals on tape. Kirby Hanson (NOAA) discussed the errors in available solar radiation data. The various primary standards that have been used differ from each other as much as 6%, so care must be taken in comparing data from different instruments. Instruments which are being used degrade by as much as 20% - 30% before being replaced, so measured intensities can be 20% to 30% low for this reason. Some sites, however, have very good data with an accuracy of 2 to 3%. R. Himberger (NOAA) described the availability of data, and the form that is available from the National Weather Service. Much of the data is hourly data on tape or cards, and a data format manuel is also available. Hourly or daily data are no longer published in printed form at the national level, but only in card, tape or microfilm form. Differences between monthly average sunshine may differ about 40% from year to year and typically 20% to 30% from site to site. There may be large differences between nearby sites due to local weather differences. Also, there can be sizeable differences from year-to-year because of changes in atmospheric turbidity.

Efforts are underway to relate reflected solar radiation to ground level incident radiation so that satellite measurements can be made useful for terrestrial solar energy generation. Absolute deviation of measurements of the solar constant vs. wavelength is less than 5%, using spectral radiometers. Surface albedo is determined by taking the 15 day minimum value of reflected sunlight measured by the satellite, and once this value is determined, it can be used to evaluate incident surface radiation from satellite measurements. Satellite measurements should provide very useful data over short time scales, but should not be extropolated over long time scales because of variations in surface albedo and atmospheric turbidity. There are several techniques for the computer enhancement of satellite pictures for the determination of insolation due to haze. Satellite measurements are essential for microscale data (resolution a few miles); interpolation between stations is not adequate for specific site studies of solar-thermal conversion, this data must come from satellites. One problem, however, is that satellites provide data on total radiation, whereas for concentrator power systems, direct beam radiation is needed. One can determine this if the cloudiness is measured, and satellites do measure cloudiness. Dr. M. P. Thekaekara (NASA/Goddard) and others at NASA made measurements of the solar spectrum and solar constant, which is 1353 + 1.5 W/m^2 outside the atmosphere.

The flat plate collector incorporates a transparent cover over a black plate with air or water flowing over or through the black plate, and is usually fixed in position. In order to evaluate their performance, one must know the intensity, angle and spectrum of solar energy as a function of time. Surface reflectivities depend on the incidence angle, and incident radiation must be split into direct and diffuse components. Liu has developed an empirical technique for doing this by using a relationship between daily total radiation outside the atmosphere to daily total at ground level.[20] He has developed a plot of hourly radiation vs. fraction of time radiation received. These statistical distribution curves are very similar for different sites of equivalent overall cloudiness. Thus far no analysis has been done on the probability of two consecuative days of cloudiness, etc., which is needed for determining storage requirements.

This type of distribution will also be about the same for different sites of the same long term average cloudiness.

Dr. Robert Schlesinger and others at J.P.L. have investigated the sensitivity of solar collector design to solar input. JPL and California Gas are evaluating the SAGE (Solar Assisted Gas Energy) system for providing hot water for apartment complexes. They determined the effect of insolation levels on collector size and cost. Water is supplied at 140^{o}F. The flat plate collectors have 2 glass sheets over a black plate containing water tubes. Collector area vs. insolation is plotted for constant system performance. 46 ft^2/apartment unit is used on a clear summer day. A 10% decrease in solar energy results in an 18% increase in area and cost; a 30% decrease doubles collector area, and increases total system cost about 50%. He said this system is designed exclusively for Pasadena, California, so the winters are not very cold.

In the tower concept for central station power generation, about a thousand separate flat mirrors spread over a one square mile area reflect light to a centrally located boiler on a tower. Each mirror must be independently steered with a heliostat to keep it oriented so that sunlight is reflected to a tower. If a small amount of haze results in significant small angle scatterings, the performance of such high concentration ratio systems would be degraded. One problem with solar cell systems is lack of insolation data. The direct component is essential for solar cells with concentrators. Concentration ratios up to 10 are feasible. The need for spectral information is not critical as long as a photovoltaic cell of the type under consideration is used for insolation measurements. JPL calibrated solar cells on high altitude balloons. Sets of solar cells with different spectral responses can be used to obtain the necessary insolation data for predicting performance of different types of cells. The cell is characterized by measurements of its short circuit current and temperature. Tests of solar cell powered buoys for navigation have been made by the Coast Guard. Going to solar powered buoys will save about $3 million per year, mainly due to the smaller number of trips out to the buoys for servicing. The solar cells are purchased from Heliotech, Centralab, Solar Power Corp (Exxon), and Sharp. Spectral as well as total insolation data are required for testing solar cells and cover materials. Covers cost from 0.1¢/ft^2 to 25¢/ft^2 depending on material. Some materials, like mylar, will degrade in the U.V. up to 0.4 microns; PVC plastic is sensitive to degradation by short wavelength UV. Transmission in the area of 0.4 microns may be important for new types of cells with short wavelength response. There is considerable uncertainty at present in insolation between 0.3 and 0.45 microns.

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SOLAR ENERGY COLLECTORS

The type of device used for the collection of solar energy depends primarily on the application. Flat plate thermal energy collectors are used for heating water and heating buildings, but can provide temperatures of only about 100°F above ambient. If higher temperatures are desired, the sunlight must be concentrated onto the collecting surface. If electrical power is to be produced, photovoltaic cells can be used to convert sunlight directly into electricity, either with or without concentrators. The decision as to what kind of collector to use for a specific application is dictated by economics.

Flat Plate Collectors

Figure 1 illustrates the basic components of a flat plate collector. A black plate is covered by one or more transparent cover plates of glass or plastic, and the sides and bottom of the box are insulated.

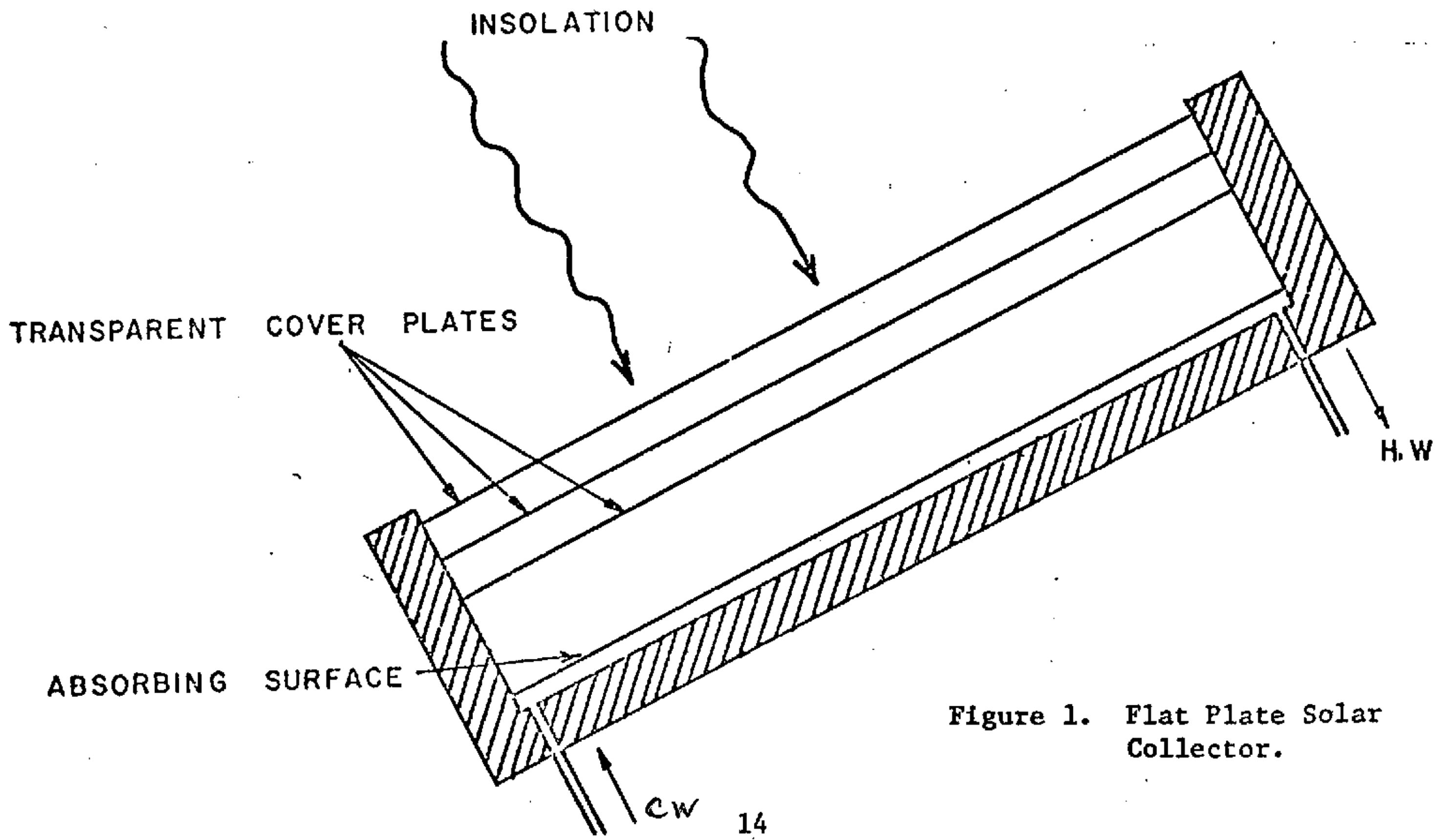


Figure 1. Flat Plate Solar Collector.

Sunlight is transmitted through the transparent covers and absorbed by the black surface beneath. The covers tend to be opaque to infrared radiation from the plate, and also retard convective heat transfer from the plate. Thus, the black plate heats up and in turn heats a fluid flowing under, through, or over the plate. Water is most commonly used, since the temperatures involved are almost always below the boiling point of water. The hot water may be used directly or may be used for space heating in homes and buildings. Kakabaev[21] tested five types of flat plate collectors and showed that the collection efficiency ranged from 40% to 60% for a 30°F temperature rise and dropped to 30% or less for a 100°F temperature rise. His collectors consisted of a wood frame with the flat black collector inside. 7 to 10 cm of sawdust were used beneath the collecting surface for insulation, and the top of the frame was covered with a single 2 mm thick window glass. The collector was a 1m x 3m steel sheet of 2.2 mm thickness containing 1 cm diameter coolant tubes 10 cm apart. The maximum incident radiation intensity was 800 Kcal/m^2 hr.

Lorsh[22] tested a collector consisting of two glass panes and a flat black metallic absorber and studied the effects of varying the air gap and the surface coating. Using air gaps between the glass panes and between glass and collector plate of 0.01, 0.02, 0.04 and 0.08 feet, he found that the best performance was with the 0.08 foot spacing, but the performance with the 0.04 foot spacing was almost as good. The performance of these collectors was considerably improved when a selective coating was applied to the collecting surface instead of flat black paint. Figure 2 illustrates the spectral reflectance of three types of coatings.[23] Such coatings strongly absorb incident sunlight, but retard

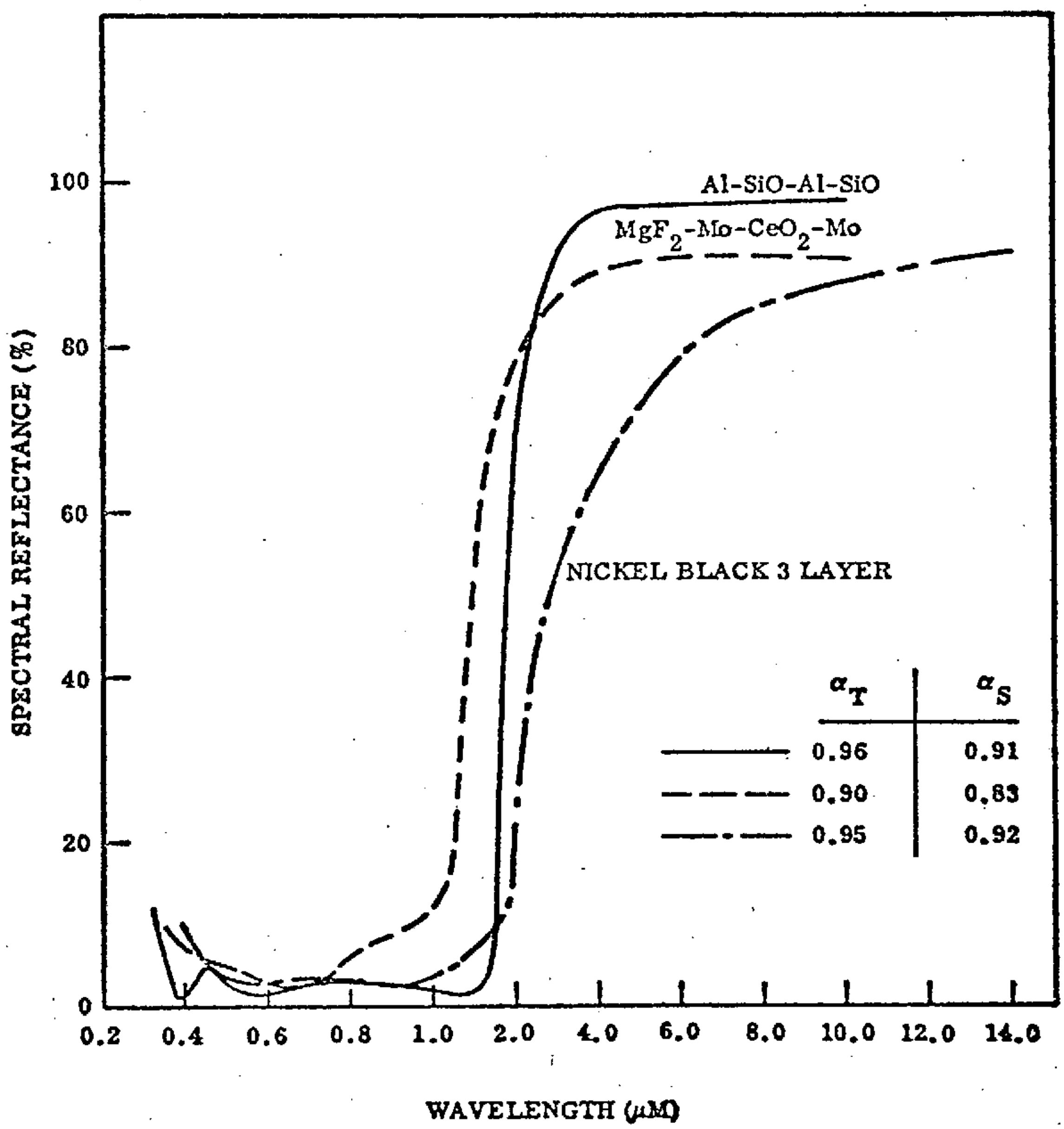


Figure 2. Spectral Reflectance of Spectrally Selective Coatings.[23]

reradiation of infrared heat, and thus allow the collecting surface to reach a higher equilibrium temperature. For a 100°F temperature difference between the outer glass and absorber the collection efficiency increased from 35% to 55% when the selective coating was added, and increased from 10% to 40% when the temperature difference was 150°F. However, the cost of the collector is also increased, so there was no major change in its cost effectiveness. The collection efficiency of duel glass plate vertical collectors was measured as a function of temperature for three insolation levels. The maximum temperature difference reached was 87°F for an insolation of 100 BTU/ft^2 hr., 153°F at 200 BTU/ft^2. hr., and 210°F at 300 BTU/ft^2 hr. The collection efficiency was about 50% at half the maximum temperature, and decreased almost linearly to 0 at the maximum temperature.

The efficiency of flat plate collectors can also be improved by anti-reflective coatings on the transparent covers. Figure 3 illustrates

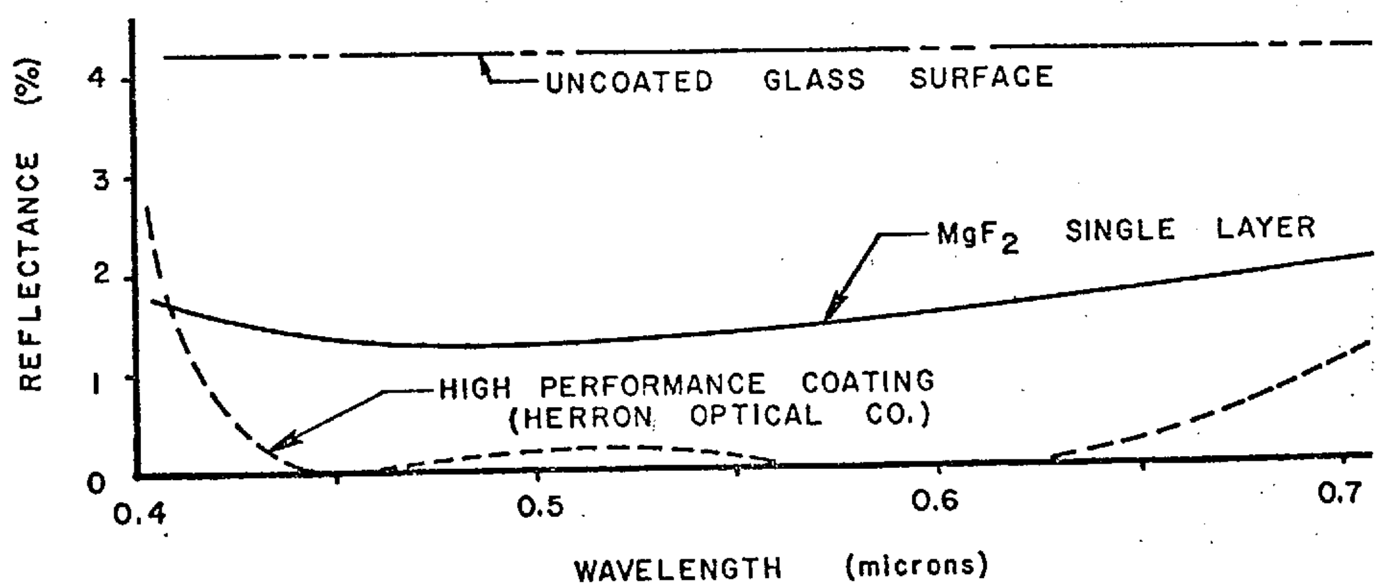


Figure 3. Reflectance of Anti-Reflective Coatings.[24]

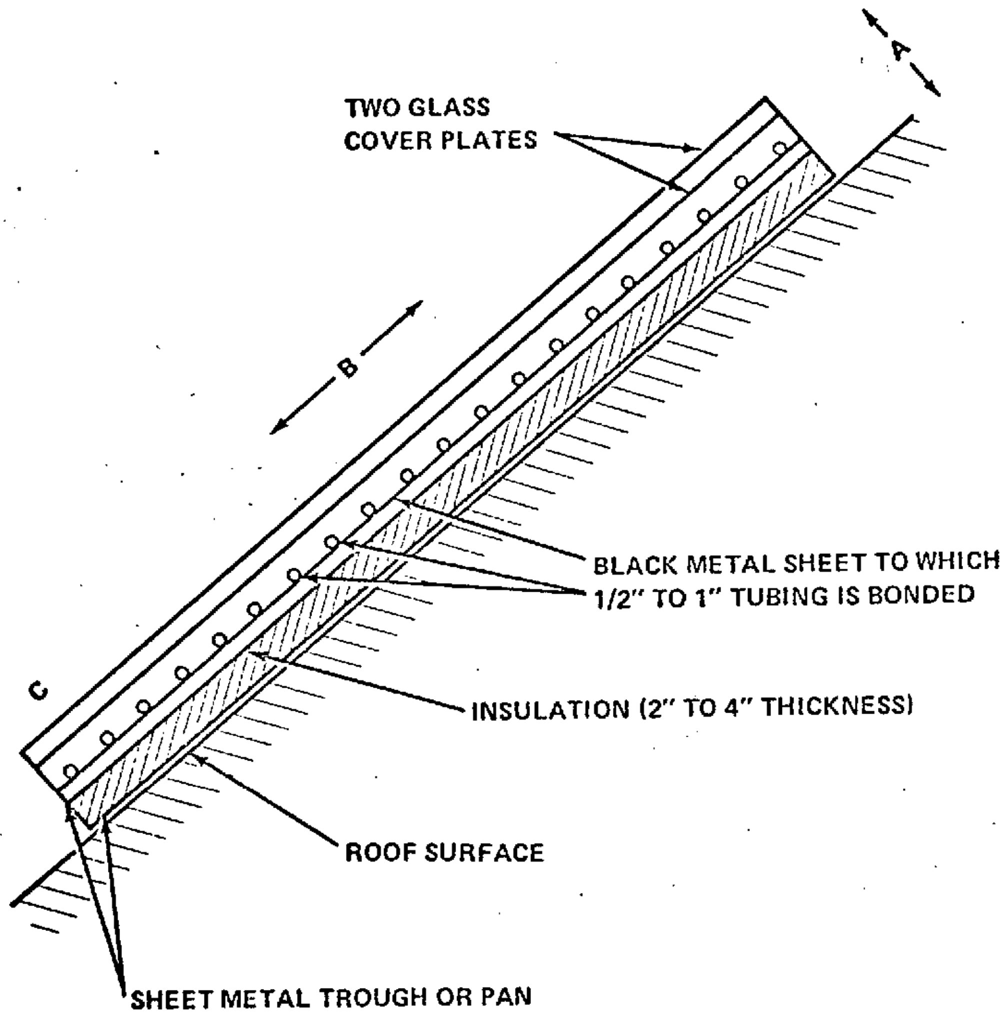
the percent of normal incidence sunlight reflected from uncoated and coated glass surfaces. Coated surfaces, of course, cost more than uncoated surfaces, and the coating cost increases as the performance increases.

Figure 4 illustrates a typical flat plate collector used to provide hot water for space heating and the operation of absorption-type air conditioners. Such collectors are placed on rooftops with a southward slope and on south-facing walls. The average daily insolation is reduced about 20% between November 21 and January 21 if the wall faces southeast or southwest instead of south, and is reduced about 60% if the wall faces east or west.[22] A flat plate collector incorporating solar cells has been developed at the University of Delaware[25] (Figure 5) to supply both electricity and heat for a house. One problem with this type of collector is the decrease in photovoltaic conversion efficiency and lifetime with increasing temperature. The 4 x 8 foot collectors are deployed between the roof joists from the inside; the outside is glased with 1/4 inch plexiglas. The heat transfer fluid for this type of collector is air.

<u>Solar Concentrators</u>

Concentrators are used to produce temperatures in excess of about 250°F for efficient electrical power generation, for industrial and agricultural drying operations, and for other applications where high temperature heat is needed. Also, concentrators have been used to increase the power output of photovoltaic cells.[26]

For high concentration the ideal form of the concentrator, from an optical standpoint, is parabolic; however in order to achieve this high concentration the reflector must be steered so as to be kept directed toward the sun, and the heat exchanger must be kept located at its focus. For this reason, parabolic concentrators are seldom considered for most solar energy applications. Large solar collectors are subject to large wind loadings, and thus require a sturdy supporting structure. The analysis of such parabolic concentrators has been discussed in detail by Teplyakov[27].



NOTES: ENDS OF TUBES MANIFOLDED TOGETHER
ONE TO THREE GLASS COVERS DEPENDING
ON CONDITIONS
DIMENSIONS: THICKNESS (A DIRECTION) 3 INCHES TO 6 INCHES
LENGTH (B DIRECTION) 4 FEET TO 20 FEET
WIDTH (C DIRECTION) 10 FEET TO 50 FEET
SLOPE DEPENDENT ON LOCATION AND ON
WINTER-SUMMER LOAD COMPARISON

Figure 4. Flat Plate Collector for Heating Water.[13]

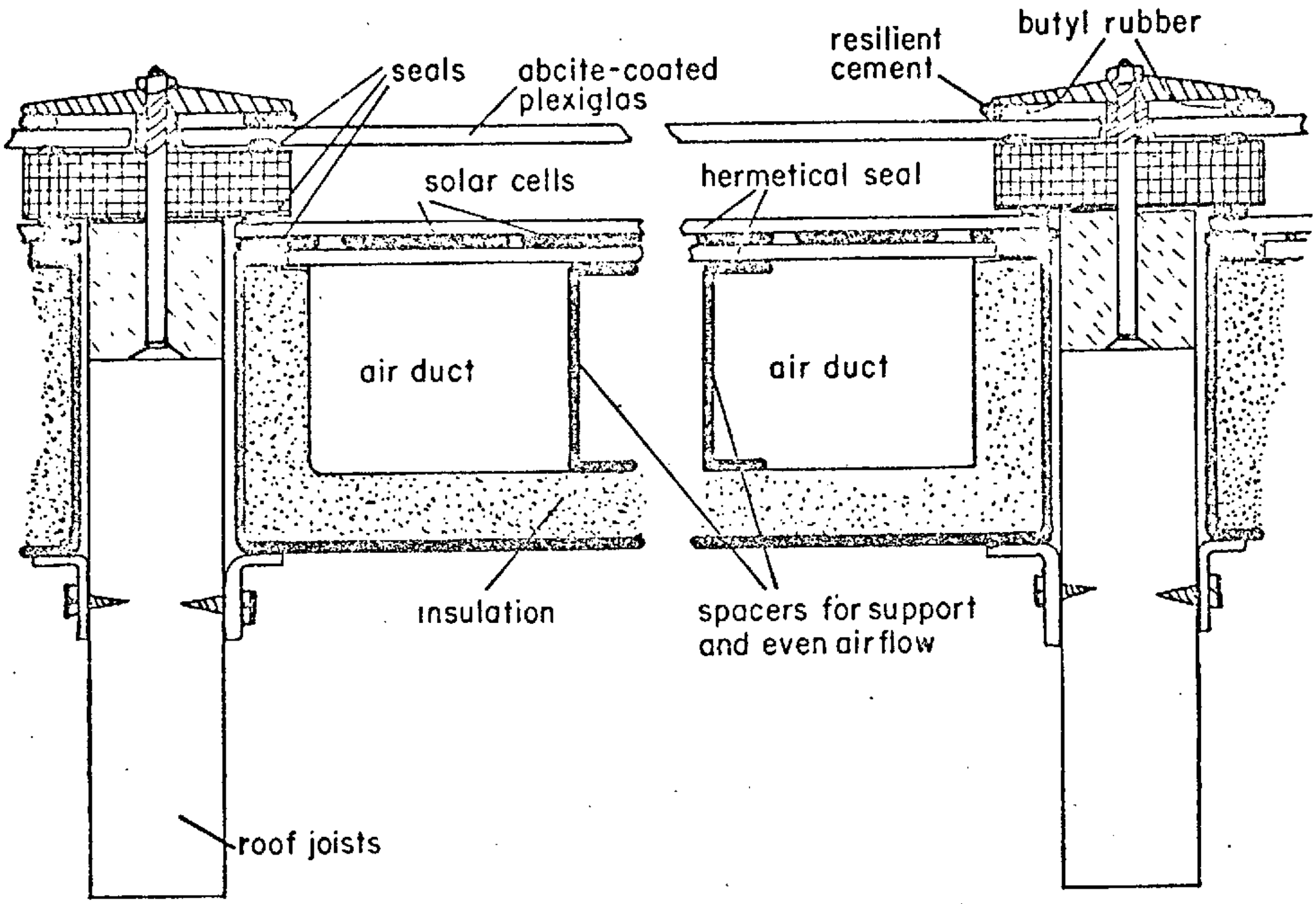


Figure 5. Cross Section of Flat Plate Collector Containing Solar Cells.

High performance concentrators can also be built using toroidal, flat or spherical components which are much cheaper to produce.[28]

One simple type of concentrating solar collector (Figure 6) uses a parabolic cylinder reflector to concentratate sunlight onto a collecting pipe within a quartz or pyrex envelope. The pipe can be coated with a selective coating (Figure 3) to retard infrared emission, and the transparent tube surrounding the pipe can be evacuated to reduce convective heat losses. The reflector is steered during the day to keep sunlight focused on the collector. This type of concentrator, known as the parabolic trough concentrator, cannot produce as high a temperature as the parabolic reflector, but produces much higher temperatures than flat plate collectors.

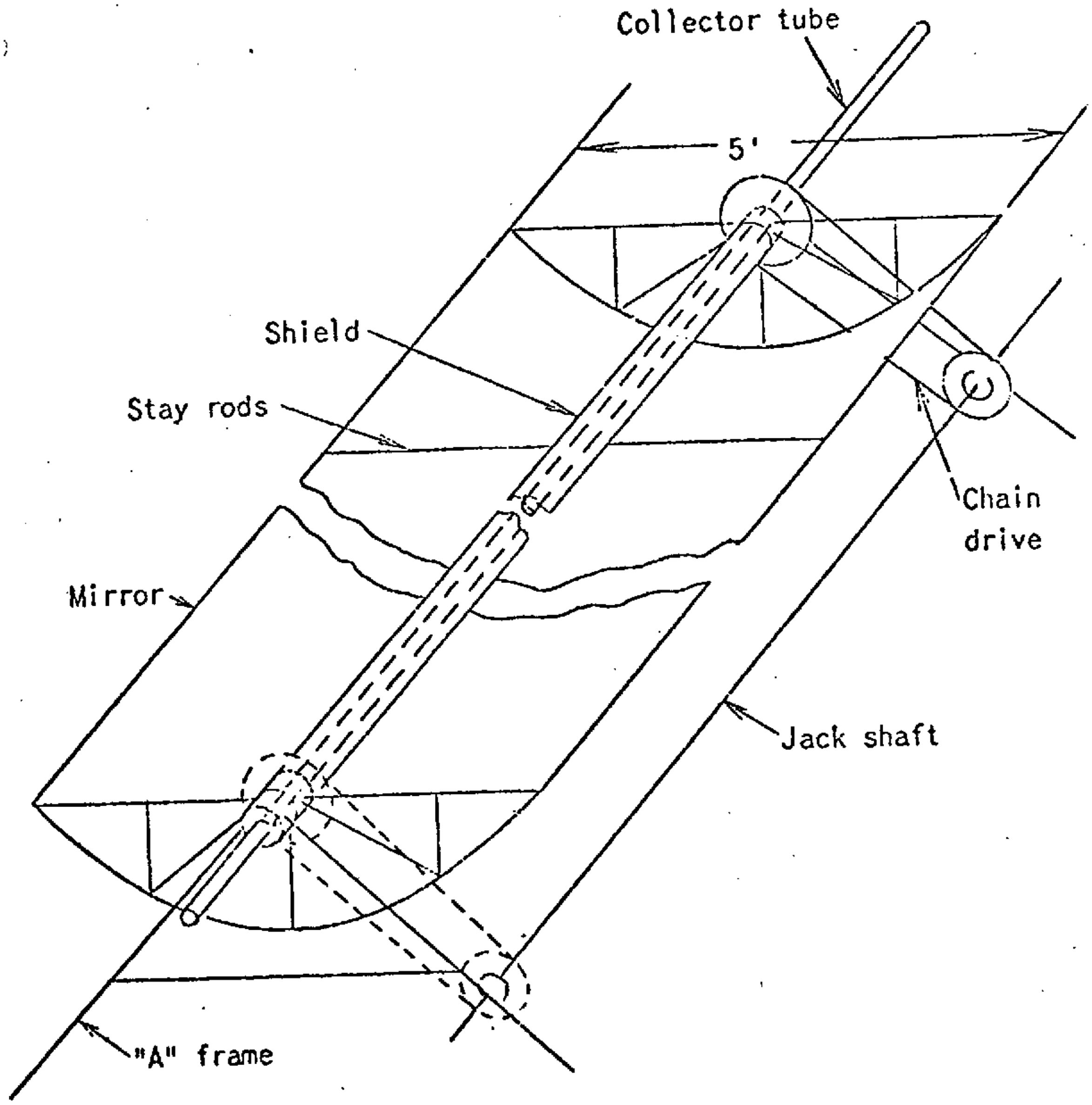


Figure 6. Parabolic Trough Concentrator.

Eibling[29] divides all solar-thermal collectors into three general categories: (1) low temperature flat-plate collectors with no concentration, (2) medium temperature concentrating collectors typified by parabolic cylinders, and (3) high concentration, high temperature collectors such as parabolic concentrators or concentrators composed of many flat mirrors focused at the same point. The following table gives the usual temperature ranges and the collection efficiencies for these three categories of collectors. The actual temperature obtained will

Table 2. Classification of Solar Collectors

Category	Example	Temp. Range	Efficiency
No Concentration	Flat Plate	150-250°F	30-50%
Medium Concentration	Parabolic Cylinder	300-800°F	50-70%
High Concentration	Parabodial	500-1200°F	60-75%

depend on the optical performance of the reflector, the accuracy of the tracking device, and the absorption efficiency of the receiver.

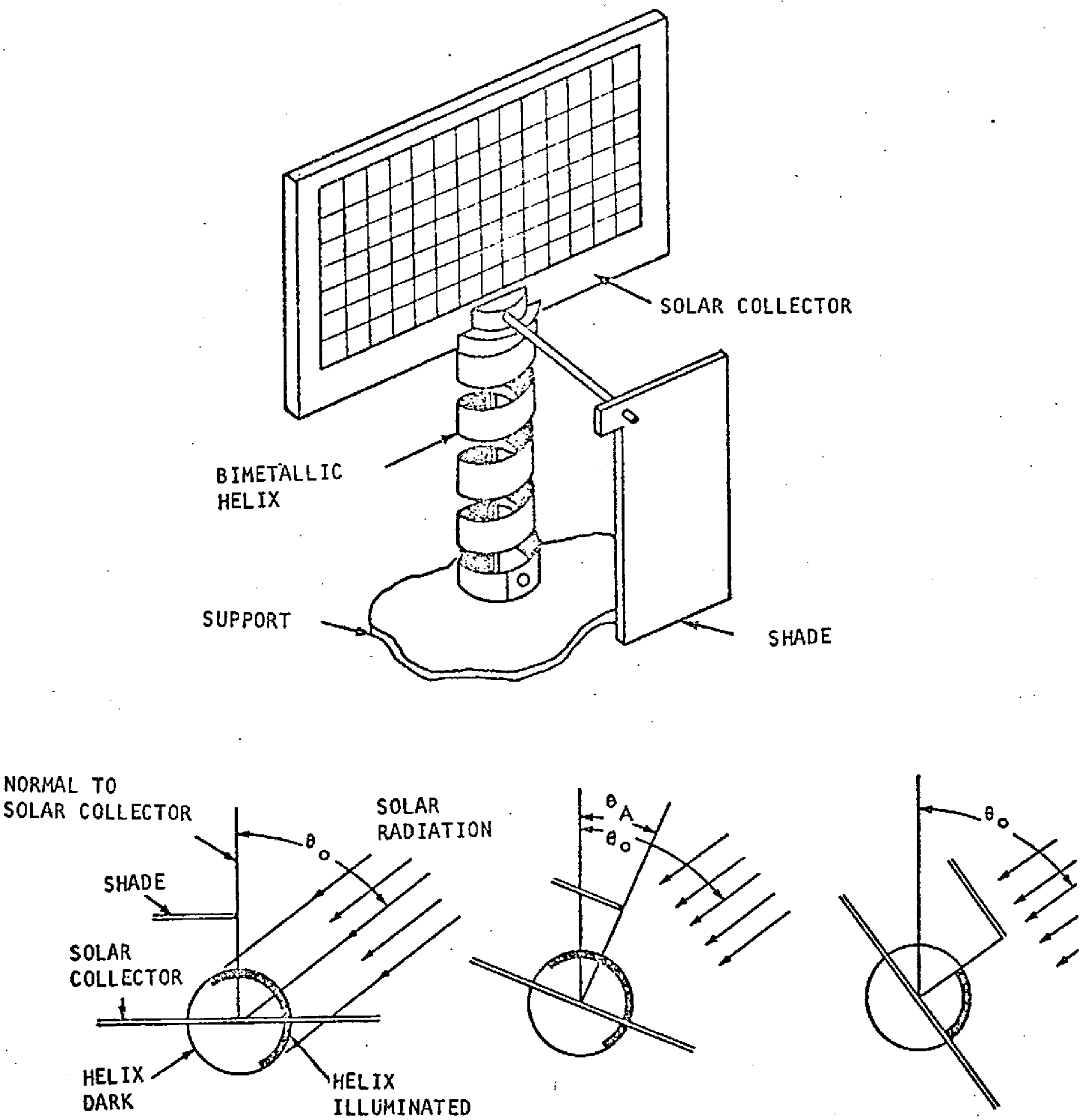
Lidoreko[30] and his colleagues in the Soviet Union have developed a technique for mass producing inexpensive faceted solar concentrators which form an approximate parabolic cylinder. They used a jig containing a number of vacuum socket facet holders, arranged along a convex cylindrical parabolic surface, all connected to a central vacuum system. In making a concentrator, the 26 mirror strips were placed face down on the correctly positioned holders and the vacuum held the mirror facets in the desired position throughout the manufacturing process. The reverse side of the mirrors was then coated with a layer of epoxy resin and covered with glass fabric. The supporting structure, which had the approximate surface shape of the finished concentrator, was placed on the glass fabric and glued to the mirror. After the epoxy had cured, the vacuum was turned off and the finished concentrator removed.

The Soviet researchers manufactured 80 concentrator sections one meter long and about one meter wide using this technique. These concentrator sections were used to make 2 power plants. It was only necessary to align the sections, and not the individual facets. They demonstrated that these concentrators were cheap to produce, had good optical characteristics, and were quite strong.

Three general approaches have been taken to try to reduce or eliminate the expense and technical difficulties associated with steering the reflecting surface: 1) develop simple, reliable, automatic steering mechanisms, 2) develop concentrators using a large number of separate reflectors, which require less supporting structure than a single large concentrator, and 3) develop fixed mirror concentrators.

One of the most promising passive steering devices for cylindrical-type concentrators and other small collectors is the thermal heliotrope, as described by Fairbanks and Morse.[31]

"In its most elemental form, the thermal heliotrope consists of a single bimetallic coil with appropriate thermal coatings and a feedback shade. This is shown schematically in Figure 7. The fixed end of the helix is attached either to the vehicle in a space application, or to a stationary support in the terrestial application. The solar array and the feedback shade are attached to the free end of the helix. The function of the shade is to regulate the amount of solar radiation incident on the helix, thereby causing the rotation of the helix to stop when the array is aligned normal to the solar vector.



(a) SOLAR COLLECTOR INITIALLY DISORIENTED WITH RESPECT TO THE SUN.

(b) SOLAR COLLECTOR ADJUSTING-SHADOW ABOUT TO FALL ON HELIX.

(c) SOLAR COLLECTOR ALIGNED WITH RESPECT TO THE SUN.

Figure 7. Thermal Heliotrope Orientation Sequence.[31]

The principle of operation may be illustrated by assuming that the sun's rays initially are at some angle θ_o with the normal to the solar cells, as shown in Figure 7a. Solar energy input to the helix causes its temperature to rise which, in turn, causes the two components of the helix to rotate - the rate and extent of rotation depending on the properties of the two components of the helix and the temperature distribution within the helix. The rotation of the free end is such that the solar array to which it is attached rotates toward the sun as shown in Figure 7b. At some angle θ_A the shade begins to cast a shadow on the helix. Further rotation of the helix causes the shade to shield a portion of the helix from the solar radiation. This decreased solar energy input reduces the rate at which the temperature of the helix was increasing which, in turn, reduces the angular velocity of the helix. A point is reached at which the net energy input to the helix is zero and the rotation ceases. At that point the solar array is aligned perpendicular with the sun's rays, as shown in Figure 7c.

The tracking feature of the thermal heliotrope may be illustrated by the situation wherein the relative position of the sun changes such that θ_o increases slightly in a clockwise direction. This change will increase the surface area of the helix illuminated by the sun's rays. The resulting increase in temperature of the helix will cause the shade to rotate in the clockwise direction until the energy balance on the helix is restored. A similar sequence of events occurs should θ_o decrease. In such a manner the solar array is able to continuously track the sun."

The bimetal considered the prime candidate for terrestrial use has a high expansion component of 72% Mn - 18% Cu - 10% Ni and a low expansion component of 36% Ni - 64% Fe, commonly referred to as Invar. This bimetal is one of the most thermally active and one of the least expensive. The thermal heliotrope is a promising passive orientation device which could probably be produced in large quantities at low unit cost, and thus reduce the cost of tracking the sun for the collection of solar energy.

Instead of steering a single concentrator, Gunter[32] proposed a faceted solar concentrator in which the separate flat reflecting facets were rotated by a single mechanism. Each facet is rotated at exactly the same speed to keep the reflected sunlight focused on a fixed heat collecting element. Another approach is to focus many separate flat mirrors onto a single point. The difficulty with this system is that each mirror requires a separate steering mechanism, but if large numbers are used, they may lend themselves to the economics of mass production.

A third approach to reducing the concentrator cost is to fix the reflector and move the heat collecting element. The problem with this is that the standard reflecting surfaces are only in focus for one sun direction. The parabolic cylinder and parabodial concentrators are only in focus when the sunlight is incident along the axis of the parabola. Thus the problem with such fixed collectors, as proposed by Steward[33], is that the focus is severely degraded whenever the incident direction of the sunlight is significantly off axis.

Recently, a new type of reflecting surface was proposed by Russell[34] which remains in focus for any incident sun angle. It is composed of long, narrow flat reflecting elements arranged on a concave cylindrical surface. The angles of the reflecting elements are fixed so that the focal distance is twice the radius of the cylindrical surface. The focus is always sharp for parallel light of any incident direction. The point of focus lies on the reference cylindrical surface, so the heat exchanger pipe can be supported on arms that pivot at the center of the reference cylinder. This greatly simplifies the positioning of the heat exchanger.

HEATING FOR HOUSES AND BUILDINGS

The Committee on Science and Astronautics of the U.S. House of Representatives has concluded[35] that "the most promising area for the application of solar energy within the next 10 to 15 years, on a scale sufficient to yield measurable relief from the increasing demands upon fossil fuels and other conventional energy sources, is the use of solar energy for space heating, air conditioning, and water heating in buildings". As is seen from Table 3, energy for space heating, air conditioning, and water heating in building services accounts for about 25% of the total energy consumption in the United States, and is presently supplied almost totally by the combustion of high quality fossil fuels. The sources which supply this energy are depicted by Figure 8. Space heating accounts for more than half of the total residential energy consumption. Space heating alone for homes and businesses accounts for 18% of all energy consumption in the United States. In the South, where solar energy is most available, practically all residential energy comes from gas or electricity, and even in the South about half this energy is used for space heating (Figure 9). Space heating and water heating account for over 2/3 of all residential energy consumption in the South.

Flat Plate Collector Systems

A typical solar heating system employing a flat plate collector is illustrated by Figure 10. A flat plate collector located on a southward sloping roof heats water which circulates through a coil in the hot water tank, then through a coil in a large warm water tank before being returned to the collector. In most areas of the country the heat transfer fluid

Table 3. ENERGY CONSUMPTION IN THE UNITED STATES BY END USE, 1960-68

(Trillions of B.t.u. and percent per year)

Sector and end use	Consumption 1960	Consumption 1968	Annual rate of growth (percent)	Percent of National total 1960	Percent of National total 1968
Residential:					
Space heating	4,848	6,675	4.1	11.3	11.0
Water heating	1,159	1,736	5.2	2.7	2.9
Cooking	556	637	1.7	1.3	1.1
Clothes drying	93	208	10.6	.2	.3
Refrigeration	369	692	8.2	.9	1.1
Air conditioning	134	427	15.6	.3	.7
Other	809	1,241	5.5	1.9	2.1
Total	7,968	11,616	4.8	18.6	19.2
Commercial:					
Space heating	3,111	4,182	3.8	7.2	6.9
Water heating	544	653	2.3	1.3	1.1
Cooking	98	139	4.5	.2	.2
Refrigeration	534	670	2.9	1.2	1.1
Air conditioning	576	1,113	8.6	1.3	1.8
Feedstock	734	984	3.7	1.7	1.6
Other	145	1.025	28.0	.3	1.7
Total	5,742	8,766	5.4	13.2	14.4
Industrial:					
Process Steam	7,646	10,132	3.6	17.8	16.7
Electric drive	3,170	4,794	5.3	7.4	7.9
Electrolytic processes	486	705	4.8	1.1	1.2
Direct heat	5,550	6,929	2.8	12.9	11.5
Feedstock	1,370	2,202	6.1	3.2	3.6
Other	118	198	6.7	.3	.3
Total	18,340	24,960	3.9	42.7	41.2
Transportation:					
Fuel	10,873	15,038	4.1	25.2	24.9
Raw materials	141	146	.4	.3	.3
Total	11,014	15,184	4.1	25.5	25.2
National Total	43,064	60,526	4.3	100.0	100.0

Note: Electric Utility consumption has been allocated to each end use.
Source: Patterns of Energy Consumption in the United States (14)

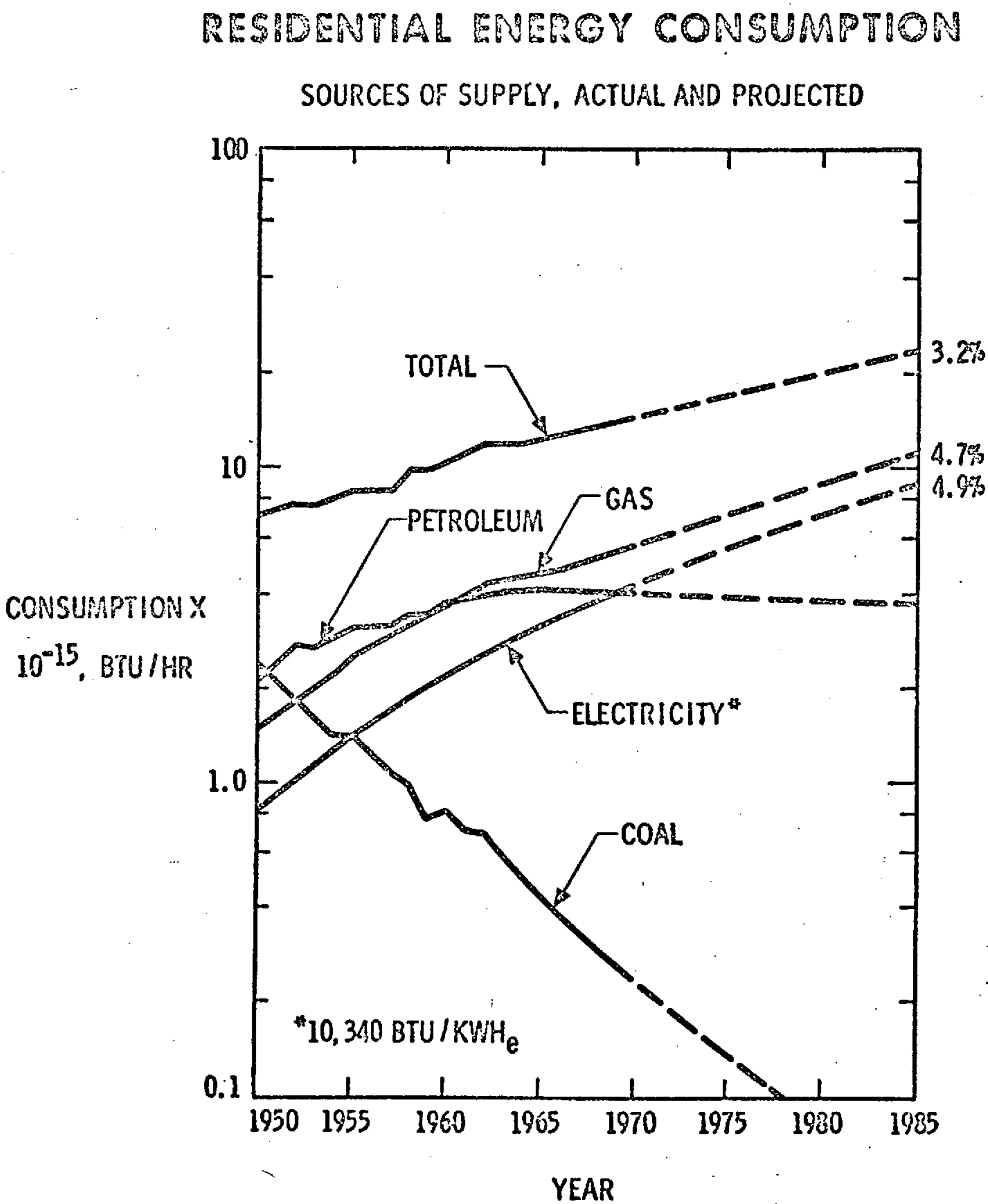


Figure 8. Sources of Residential Energy[36]

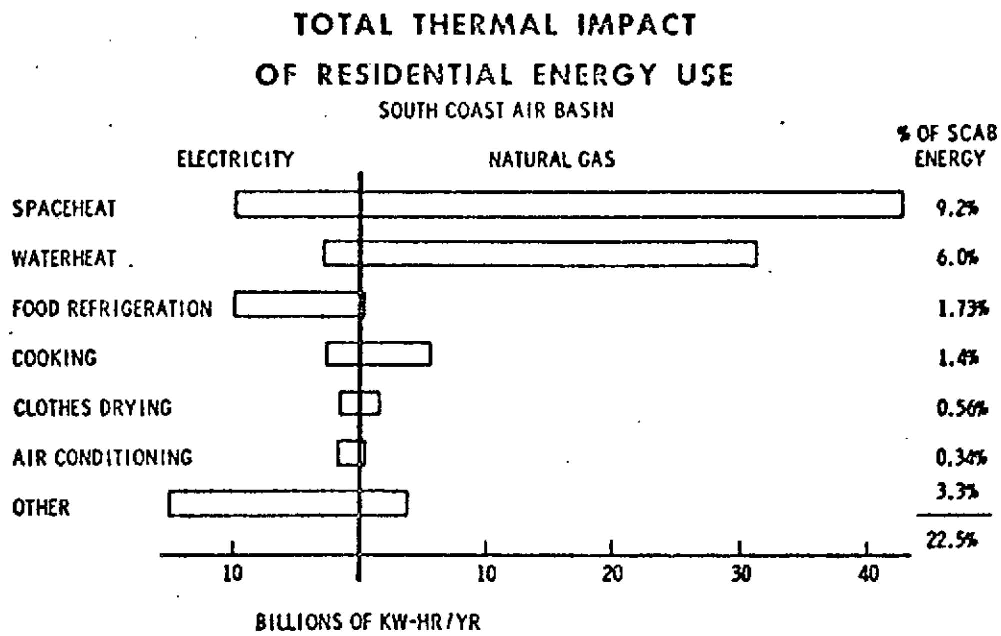


Figure 9. Residential Energy Use in the South[36]

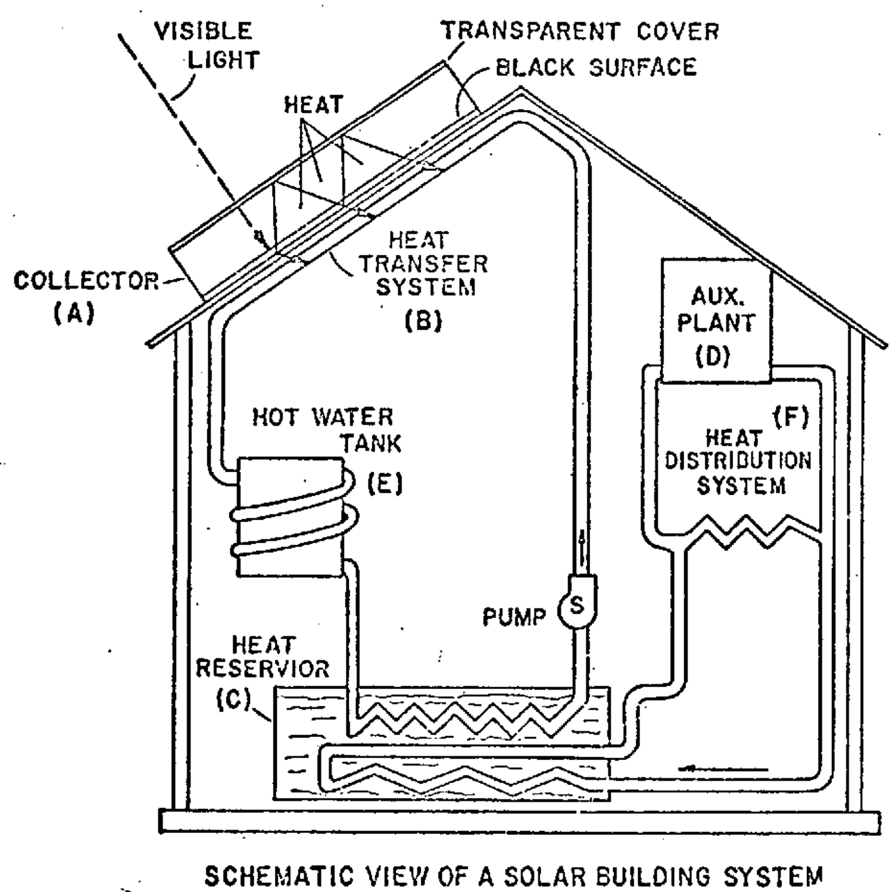


Figure 10. Solar Heating System for a Building[35]

flowing through the collector should be an anti-freeze solution to prevent freezing of the fluid in the collector tubes in the winter. The system shown in Figure 10 provides for two levels of heat storage; the hottest water which is stored in the hot water tank is used for building services, and the warm water in the large tank heats water circulating through pipes in the house. The heat reservoir for a single dwelling could be a 10 foot diameter tank, four feet deep, insulated on all sides. An auxiliary heating system is necessary to provide heat during extended cold cloudy periods when the supply of solar heat is not adequate.

Tybout and Lof[37] calculated the 1970 cost of solar space heating, and compared the cost of solar heating with gas, oil and electric heating costs by amortizing the solar system capital cost over 20 years at 6% interest. Solar heating costs were calculated for present $4/ft^2 flat plate collectors and for anticipated near-term collector costs of $2/ft^2. The results of these calculations for eight U.S. cities are given in the following table.

Table 4. Costs of Space Heating in 1970 Dollars/MBTU

Location	Optimized solar heating cost in 25,000 BTU/degree-day house, capital charges @ 6%, 20 years		Electric heating, usage 30,000 kwh/year	Fuel heating, fuel cost only	
	Collector @ $2/ft.^{2}	Collector @ $4/ft.^{2}		Gas	Oil
Santa Maria	1.10	1.59	4.28	1.52	1.91
Albuquerque	1.60	2.32	4.63	0.95	2.44
Phoenix	2.05	3.09	5.07	0.85	1.89
Omaha	2.45	2.98	3.25[3]	1.12	1.56
Boston	2.50	3.02	5.25	1.85	2.08
Charleston	2.55	3.56	4.22	1.03	1.83
Seattle-Tacoma	2.60	3.82	2.29[2,3]	1.96	2.36
Miami	4.05	4.64	4.87	3.01	2.04

Notes: [1]Electric power costs are for Santa Barbara, Electric power data for Santa Maria were not available.
[2] Electric power costs are for Seattle.
[3] Publicly owned utility.

Since these data were compiled, interest rates have increased but so have fossil fuel and electricity prices, so the general conclusions are still valid. According to Lof[15], "The two major accomplishments in this study are (1) the optimization of the design of a solar heating system and its major components, and (2) the establishment of realistic costs of solar heating in comparison with conventional heating under a variety of conditions. Both objectives have been achieved by methods which can be applied to buildings of any size and construction in any location where adequate weather data are available.

Collector size for minimum solar heat cost for a 25,000 BTU/degree day (BTU/DD) house in six locations was found to range from 208 sq ft (Charleston, S.C.) to 521 sq ft (Omaha, Nebraska), corresponding to 55 percent of the respective annual heating loads. In Santa Maria, California. a 261 sq. ft. collector can supply 75 percent of the annual heat requirement. In most situations, the cost of solar heat near optimum levels is rather insensitive to collector size and the corresponding fraction of load carried. Costs rise sharply, however, if designs are based on carrying large fractions (over 90 percent) of the load. In structures having smaller or larger heat demands than 25,000 BTU/DD, optimum collector size is approximately proportional to the demand parameter.

Heat storage capacity for minimum solar heating cost in nearly all practical situations is 10 to 15 pounds of water (or its thermal equivalent) per square foot of collector. This is the equivalent to one to two days average winter heating requirement. Solar heating cost is not very sensitive to storage capacity in this general range.

Two glass covers in the solar collector yield minimum solar heating cost in nearly all locations. One cover is optimal in the warmer climates represented by Phoenix and Miami. Heating costs are the same for one or two covers in climates such as Albuquerque and Santa Maria. Collector tilt for minimum solar heat cost is 10 to 20° greater than the latitude, but there is only a slight variation in cost over a range of inclinations between the latitude angle and 30° higher than the latitude. Variation in thermal loss from storage (located in the heated space), within the range of practical design, has negligible effect on solar heating costs and is not a factor in optimizing design. Variation in heat capacity of the collector, within practical ranges, has negligible effect on solar heating costs and is not a factor in optimizing design.

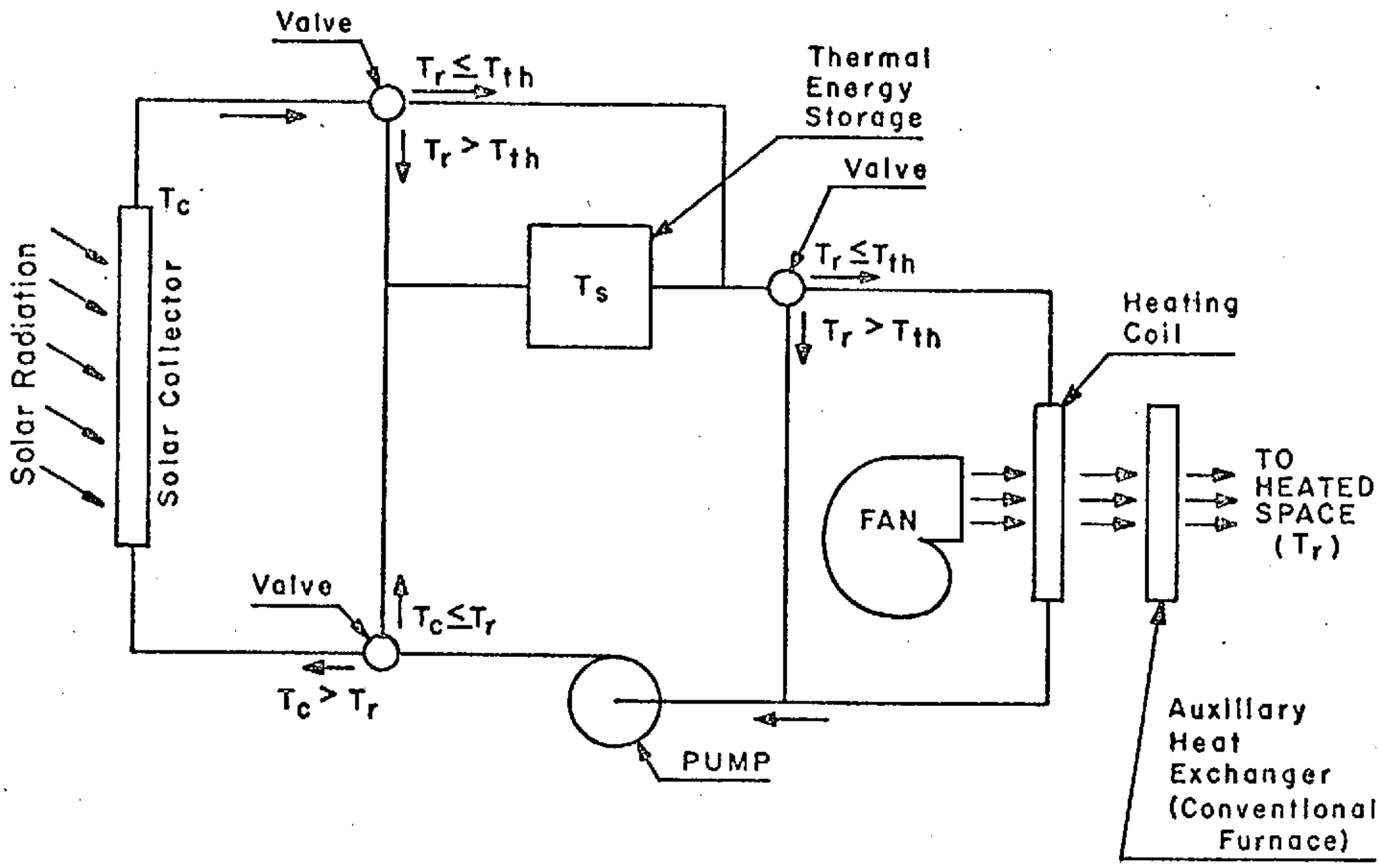
The cost of solar heat in systems of optimum design is usually in the range of two to three dollars per million BTU, and substantially below the cost of electric heat in six of the eight locations examined. Low electricity price in Seattle and low demand for space heating in Miami reverse this situation. In comparison with gas and oil heating, solar is now more expensive in six of the eight locations analyzed. But in Santa Maria and Albuquerque there are combinations of solar and fuel systems which involve total costs equal to or below those of corresponding conventional heating. In six of the eight cities there are optimum (minimum costs)combinations of solar and electric heating, the best mix being obtainable by determining marginal costs of increasing the solar heat proportion. The portion of total load supplied by solar under these conditions generally lies between 60 and 90 percent. Rising costs of heating with oil and gas are approaching solar heating costs in U.S. areas of large population. It is probable that solar heating costs will decrease somewhat as improvements are made. Competitive solar heat will become increasingly possible as these trends continue. Conditions conducive to economical solar heating are moderate to severe heating requirements, abundant sunshine, and reasonably uniform heat demand during the period when heat is needed. The higher the cost of conventional energy for heating, the more competitive a solar-conventional combination becomes".

Eibling[29] analyzed the materials cost for a flat plate collector using a single glass cover, water as the coolant, and polyurethane foam insulation, and a collector efficiency of greater than 50% at outlet temperatures up to 200°F. The materials cost on a production basis was determined to be between \$1.15/ft^2 and \$1.90/ft^2, (Table 5) which supports Lof's total cost estimate of \$2 to \$4 per square foot.

Table 5. Materials Cost for a Flat Plate Collector[29]

Component	Material	Cost \$/Ft^2
Substrate/heat exchanger	Aluminum or steel	0.60 to 0.90
Cover plate	Glass	0.25 to 0.30
Thermal insulation	Polyurethene	0.25 to 0.35
Selective coatings	Oxides, coatings	0.05 to 0.35
Total		1.15 to 1.90

Several studies have been conducted to determine optimal control systems for solar home heating systems, such as the one illustrated by Figure 11. The main object of the control system is to extract heat from the solar collector when it is available, but to shut off the flow through the collector whenever the collector temperature drops below the storage temperature. In this system a separate auxiliary heater is provided. The pump circulates water through the collector whenever the collector outlet temperature exceeds the storage temperature. If the room temperature is lower than both the collector temperature and the thermostat setting, water from the collector is circulated directly



T_c = Collector temperature

T_r = Room temperature

T_s = Thermal energy storage temperature

T_{th} = Room thermostat setting

Fan Control: Same as for Conventional Heating System

Pump Control: On: $T_r < T_{th}$ and $T_c > T_r$

or: $T_r < T_{th}$ and $T_s > T_r$

or: $T_c > T_s$

Auxiliary Heater: On: $T_r < T_{th}$ and Pump is off

Figure 11. Control Circuit for Solar Heating System.[38]

through the heating pipes in the house. If the room temperature is lower than both the thermostat setting and the storage temperature, but higher than the collector temperature (such as at night), hot water from the storage tank is circulated through the room. Thus, the solar heat is transfered directly to the room if the room is too cool, and is transfered to the storage tank for later use if the room is already warm enough. This is a fairly standard type of solar thermal control system using a single water pump and three valves. The hot water coil for heating air (like an automobile radiator) can be installed in a conventional forced air furnace.

An 8000 sq. ft. solar heating building has been designed for the Massachusetts Audubon Society[39] which uses a two-pane 3500 sq.ft. flat plate collector facing south at an angle of 45°. Figure 12 shows preliminary plan and elevation sketches and Figure 13 shows the proposed solar building and the current headquarters building. Based on the results of Tybout and Lof[37] it is estimated that the flat plate collector heating system should account for between 65% and 75% of the total seasonal heating load.

Thomason[40,41] has reported results of 13 years of operation of a solar heated house which was maintained within a few degrees of 70°F year round, with up to 95% of the heat per year supplied by solar energy. As reported by Thomason, "during 13 yr. of operation, the solar energy system has supplied most of the heat requirements for the house despite half-cloudy winter weather and temperatures well below zero Centigrade (often between 0° and 32°F). Additionally a substantial portion of the domestic water heating was achieved by solar heating. Water from the 1600 gal. steel tank is pumped to the top of the solar heat collector. There it is distributed

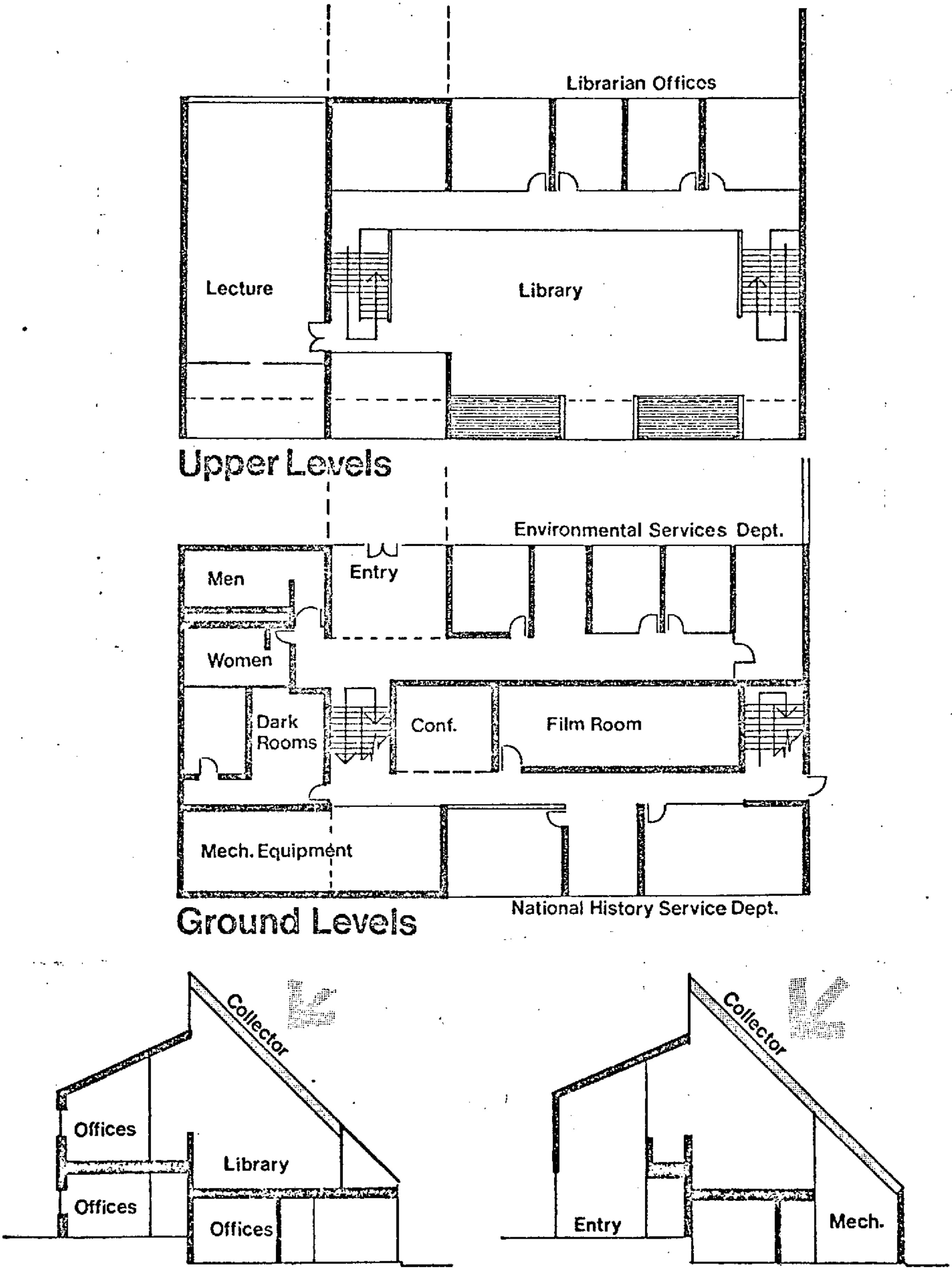


Figure 12. Plan and Elevation Sketches of Proposed Solar Building.[39]

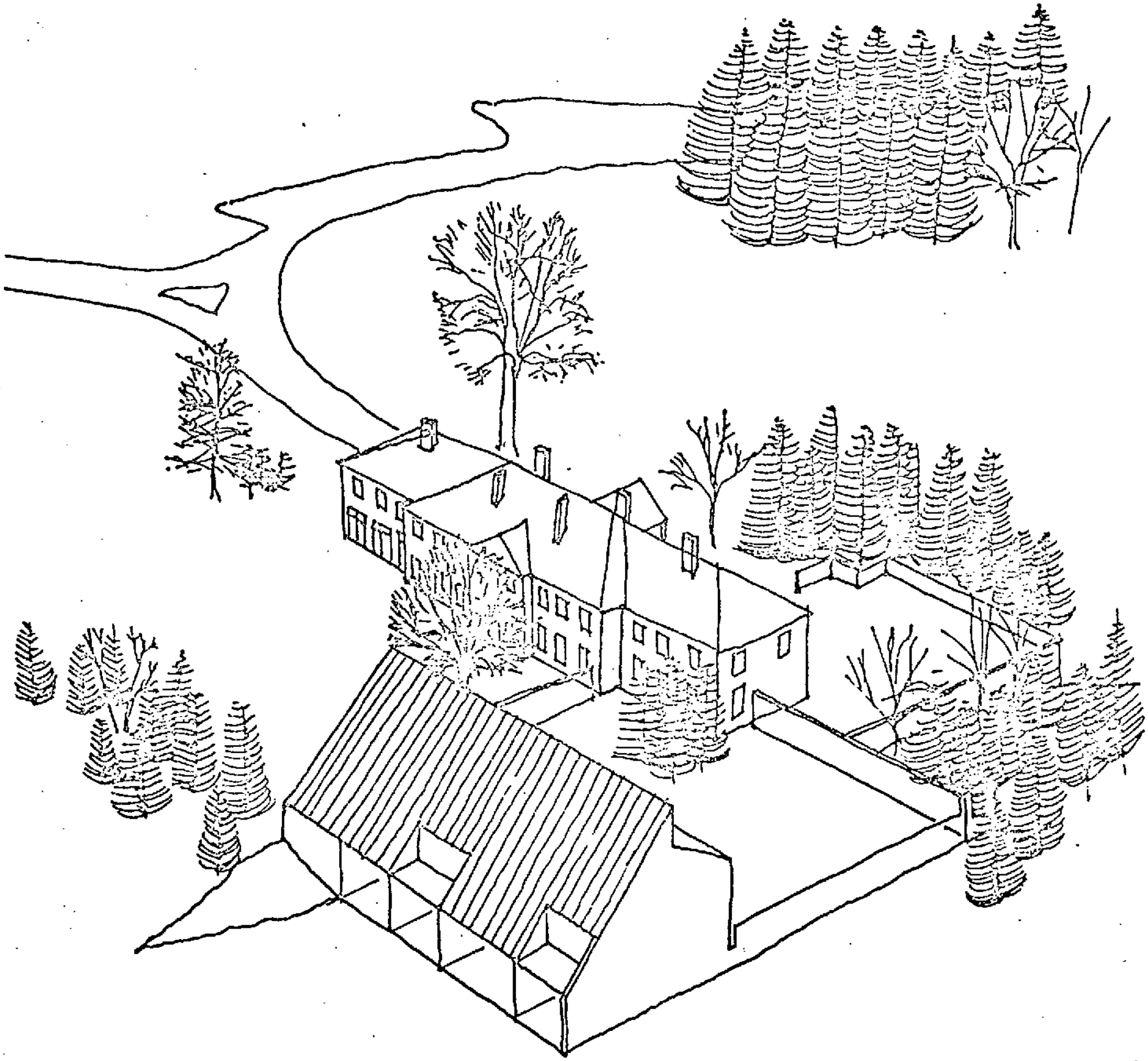


Figure 13. Proposed Solar Building and Existing Building.[39]

in small streams to hundreds of valleys on the black corrugated solar heat collector sheet. As the water flows down in the valleys it is warmed by solar energy passing through the transparent cover. A gutter at the bottom collects the small streams of warm water and passes it to a 275 gal. domestic water preheater tank and thence to the main tank in the heat storage bin. The warmed water, in addition to pre-heating the domestic water, also warms the three truckloads of fist-sized stones around the main 1600 gal. tank. Then, when the living quarters need heat, a thermostat automatically starts a 1/4 h.p. blower. This blows air through the warmed stones and around the warm tank of water thus warming the air. The warmed air passes into the living quarters. When the living quarters are warmed sufficiently, the thermostat automatically stops the blower leaving the reserve stored heat in the heat storage bin for future use. (The stored heat has kept the home temperature at 70^{o}F, plus or minus 2^{o}F, for about four cloudy days in mid-December). During the hot summer, water was pumped at night up to the north-sloping roof section. The tank of water and surrounding stones were thereby cooled. Then a reverse-acting thermostat turned the blower on to circulate air to the bin and thence to the living quarters to cool them".

Flat plate collectors are also used for heating air to over 100^{o}F above ambient for house heating. Water is usually used because of the simple storage system, which is just an insulated tank. Close[42] analyzed a variety of different types of air heaters. The simplest is a flat black plate covered by a transparent sheet, with air flowing in the gap between. However, higher temperatures are achieved if the air flows through or beneath the black absorbing surface, and the air gap beneath the transparent cover and plate is stagnant. A good collecting surface is a V-corrugated absorber plate with a spectrially selective coating (absorptivity 0.80 in the visible, 0.05 in the infrared). Absorbers of this type heated air to 170°F with 40% collection efficiency for an insolation of 160 BTU/ft^2.hr and an ambient dry bulb temperature of 74.6°F. For an insolation of 300 BTU/ft^2.hr a temperature of 210°F is reached with 40% collection efficiency. The maximum temperature of the air can be increased from 10 to 15°F with no loss in collector efficiency by allowing the air to flow over the absorbing surface and then back under the absorber (2 passes) instead of the standard single-pass configuration.[43]

Concentrator Systems

Concentrators offer several advantages for the heating of buildings:

1. Higher collection efficiencies result in smaller collectors
2. More compact heat storage
3. Year round collection of high temperature heat
4. More efficient operation of absorption cooling devices

Also, higher temperature heat collection makes the generation of electric power possible, with waste heat used for space heating and air conditioning.

When concentrators are used, water is no longer an acceptable heat transfer fluid so air or a commercial heat transfer fluid is used. At present, steering devices to keep concentrators oriented toward the sun are probably too expensive for home use. Steward[33] proposed a 962 ft^2 fixed cylindrical reflector to collect heat at 500°F. Russell's[34] fixed mirror concentrator has the additional advantage of remaining in sharp focus for all incident sun angles, permitting the efficient collection of heat at 500°F or more during most of the day. If air is used as the heat transfer medium, it can be circulated directly through a gravel tank for heat storage. Air is then brought from the gravel tank to the house, as required, for heating and other applications. Even more compact heat storage is possible with phase-change materials such as Glauber's salt (sodium sulfate decahydrate, Na_2SO_2-$10H_2O$). Telkes[44] has compared water, rocks and a typical phase-change material as follows:

Table 6. Thermal Storage of One Million BTU with 20°F Temperature Change

	Water	Rocks	Phase Change Material
Specific Heat (BTU/lb°F)	1.0	0.2	0.5
Heat of Fusion (BTU/lb)	-	-	100
Density (lb/ft^3)	62	140	100
Weight (lb)	50,000	250,000	10,000
Volume (ft^3) with 25% passage	1,000	2,150	125

Water can store heat over a range of temperatures approaching 200°F, and rocks can store heat (or coolness) at any conceivable temperature, but phase change materials melt and solidify at one temperature. Thus rocks and water can store heat in the winter and "coolness" in the summer, whereas two separate salt systems would be required to accomplish this. Phase change materials also cost more per BTU of heat storage than water or rocks. The great advantages of the phase change material are, of course, considerably reduced weight and volume.

Roof Ponds

Perhaps the simplest technique for heating and cooling a house is to locate a pond of water 6 to 10 inches deep on the roof. The pond is covered by thermally insulating panels which can be open or closed. In the winter all the water is enclosed in polyethylene bags atop a black plastic liner. Sunlight heats the water to about 85°F during the day. At night, the insulating panels are lowered to prevent loss of the heat to space. During the summer, the insulating panels are open at night and closed during the day, so the water is cooled by radiation to space at night. Hay[45] reported the results of tests with a small 10 foot by 12 foot structure in Phoenix, Arizona, where temperatures were maintained close to 70°F year round by "pulling a rope twice a day"[20], even though ambient temperatures ranged from subfreezing to 115°F. A new two bedroom house[46] with a 10 inch roof pond is now under construction (Figure 14) in California at Atascadero near Paso Robles

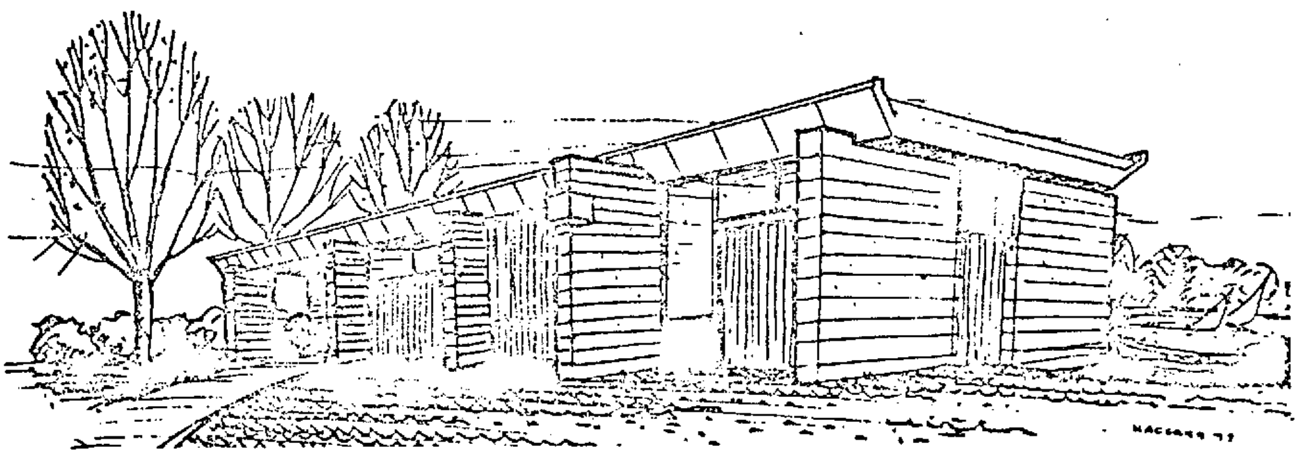


Figure 14. Solar Heated House with Roof Pond.[47]

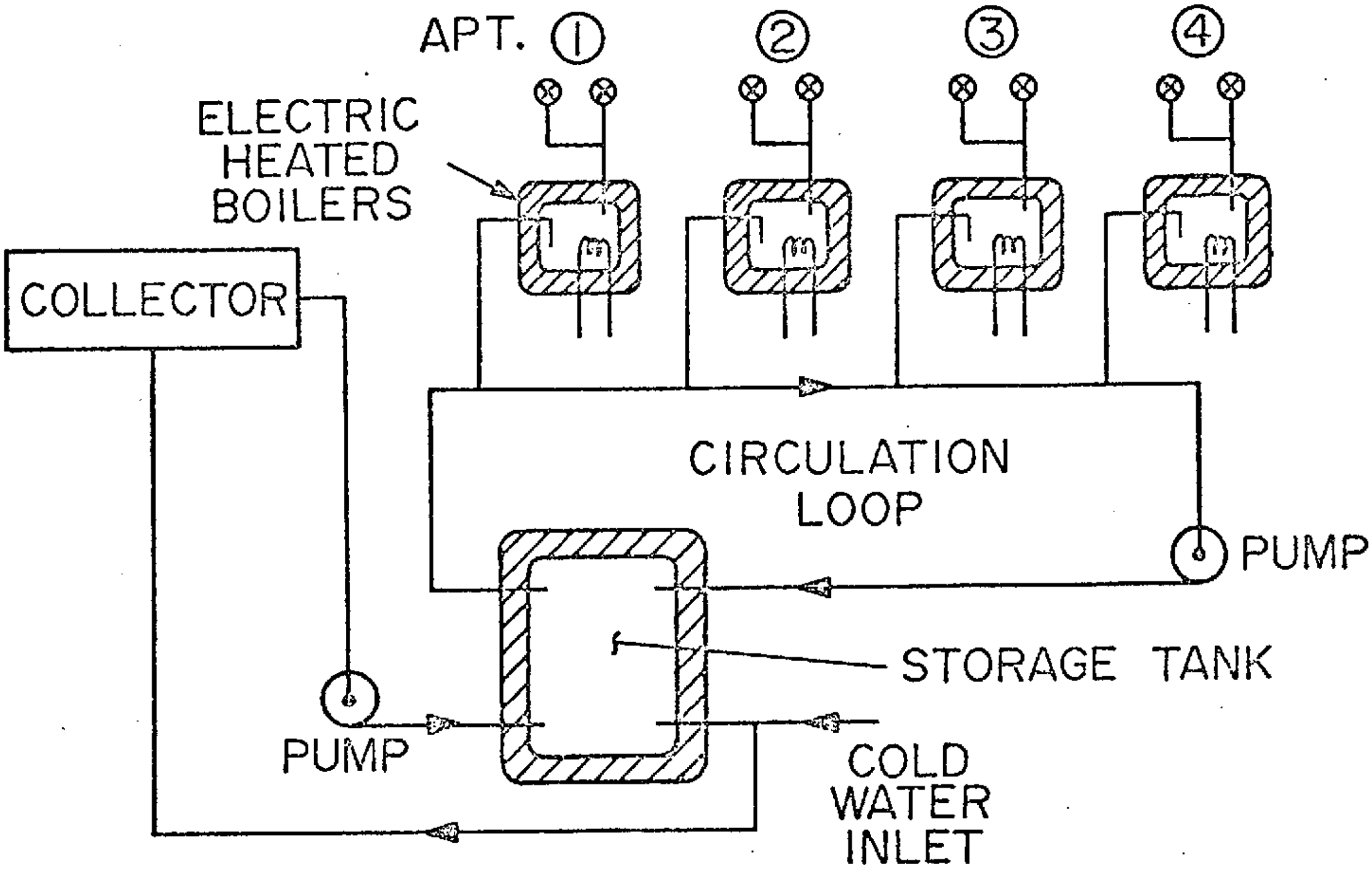
which has recorded temperature extremes of 10°F and 117°F. This horizontal roof collector is not expected to meet the full heat demand because ambient air temperatures are lower, cloud cover is greater, and the location is two degrees more northerly than the Phoenix location of the test room. Summer cooling, however, should be better than at the Phoenix location. The roof pond is not visible at ground level. The house is to be occupied for one year while it is evaluated by professors from Cal. Poly University with financial support from HUD.[47]

SOLAR WATER HEATERS

Solar water heaters are currently in widespread use throughout many sunny areas of the world. A common arrangement is to have a flat plate solar collector on the roof which provides hot water by natural circulation to a tank located higher on the roof. The roof tank can be designed to look like a chimney. In Japan there are about 2 1/2 million solar water heaters of several different types currently in use [48]. The Japanese units employ a storage tank and collector as an integral unit, whereas in other countries the storage tank is usually separated[49]. The simplest and oldest type is a flat open tank on the roof, costing about \$10 with a black bottom, which supplies water at 130°F in the summer and as high as 80°F in the winter. Since the water is sometimes contaminated by dust, a polyethelene film covering the tank can be added for a few dollars additional cost. The transparent cover lasts about three years, and increases the water temperature as well as preventing contamination. The standard heater size is about 3 feet wide, 6 feet long and 5 inches deep. These flat tank type water heaters are cheap, but suffer a major disadvantage in that they must be mounted horizontally, so they are not very effective in the winter when the sun is low. Closed pipe collectors can be mounted at a more optimum angle to the sun and thus provide hotter water during the winter months. The pipes are made of glass, plastic or stainless steel painted black mounted in a frame covered with glass or transparent polyethelyne plastic. The cost of these units range from \$100 to \$200. The purchasing of solar water heaters has declined since 1967 because of the availability of convenient and inexpensive heaters using fuels such as propane gas, however the recent rapid escalation of fuel prices will probably result in another increase in solar water heater sales.

In the United States about 60-70 square feet of collector can supply 75% of the water heating needs of apartments. One study which is underway is Project SAGE (Solar Assisted Gas Energy)[36] in southern California which is studying the technical and economic aspects of a solar assisted gas and electric water heating system for a typical Southern California apartment building. Figure 16 illustrates a solar-electric hot water system for an apartment complex, with a single collector and storage tank. This reduces the cost of collecting the solar heat for the apartment. The cost of the solar collection and storage is part of the cost of building and maintaining the apartment building, so it is included in the rent. The electric power consumption, however, is paid for by the individual user as part of his electric bill. This aspect of the system is attractive from the viewpoint of the apartment owner since it provides accountability for the consumption of hot water during periods when the solar input alone is not adaquate. The same general type of solar collector can be used to preheat water before it enters a conventional gas water heater. Water heating in a freezing climate requires that an intermediate heat transfer fluid (antifreeze solution) circulate through the collector in a closed loop and transfer its heat to water in a heat exchanger, as is shown in Figure 17. If the collector temperature is higher than the cold water inlet temperature (which is usually the case when the sun is shining on the collector), the pump is turned on and fluid from the collector circulates through a coil in the storage tank, thus preheating the water in the tank before it enters the conventional heaters. Solar heat is thereby used year round to reduce the consumption of gas or electricity for water heating. During parts of the summer all of the heat can be supplied by the solar collector. The water flowing through the collector can also be at a lower pressure than water in the storage tank.

SOLAR ELECTRIC WATER HEATER (Design II)



NOTES:

1. INDIVIDUALLY METERED SYSTEM
2. REQUIRES BOTH < HOT WATER CIRCULATION / 220V SERVICE TO APTS.
3. SOLAR ENERGY IS INCLUDED IN THE FIXED PART OF THE BILL

Figure 16. Solar-Electric Water Heater for Apartments[36]

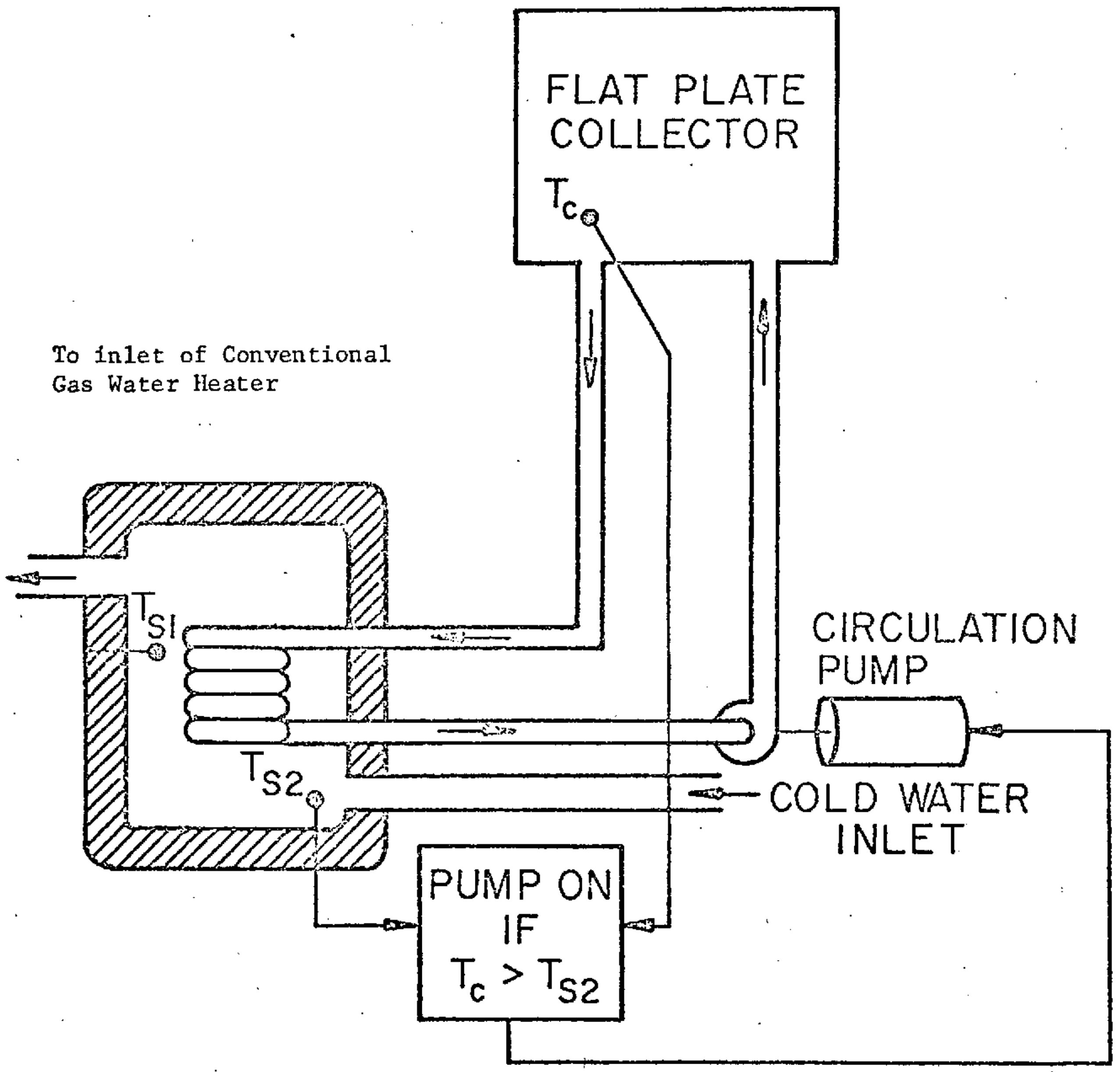


Figure 17. Solar-Gas Water Heater[36].

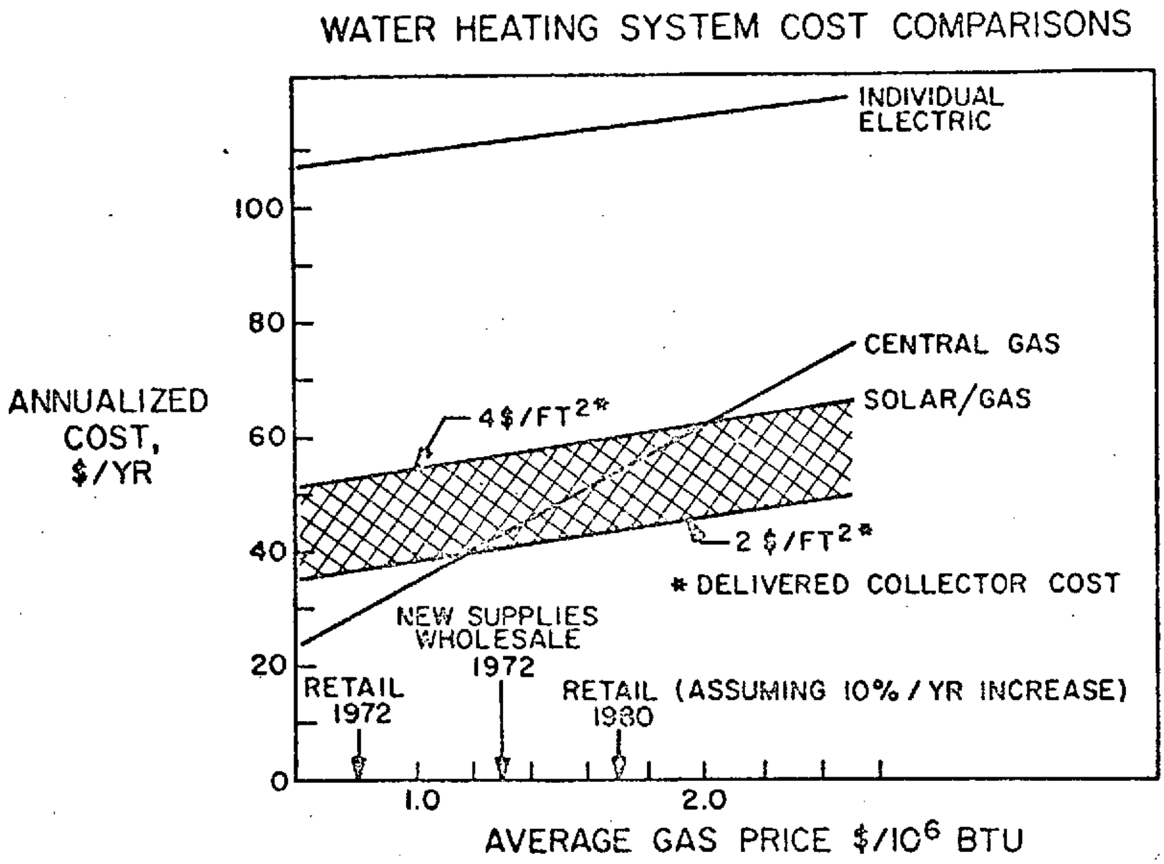


Figure 18. Water Heating Cost Comparisons.[36]

The costs of electric, gas, and solar-assisted gas water heating are compared in Figure 18. It is clear that as gas prices rise, and as solar collector costs decrease from the present $\$14/ft^2$, solar-assisted gas water heaters will become cheaper than gas heaters alone. Already, solar assisted electric heating is cheaper than electric water heating alone, because of the high cost of electric water heating. At the present time gas is not being supplied to new units, because of short supply, in some areas of the country. The cost comparisons shown in figure 18 are based on a discount rate of 10%/year, a system life of 10 years, and an apartment size of 50 units[36].

Garg [50] has reported the design and performance of a large forced-circulation water heater of the same general configuration as that considered in the SAGE study. The flat plate collector consisted of 28 guage blackened aluminium sheet attached to 1.9 cm. diameter galvanized pipe with 10 cm

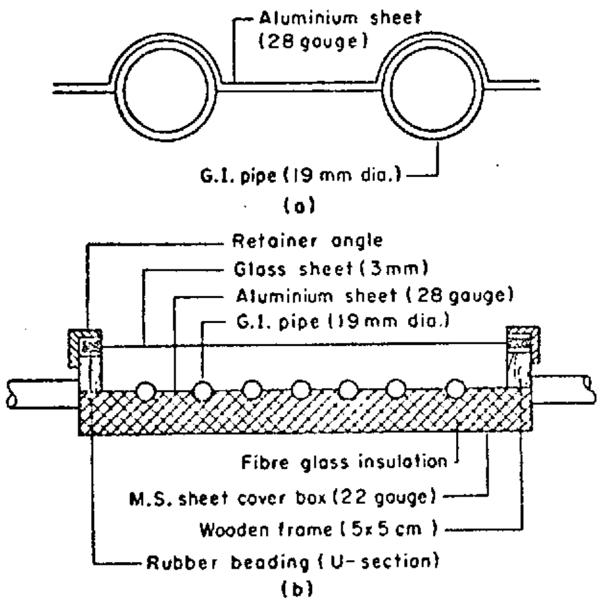


Figure 19. a) Flat Plate Collector, b) Collector Unit [50]

spacing, as shown in figure 19a. This collector configuration is optimized[51] for maximum heat collection per unit cost. A single 3 mm glass sheet covers the collector plate (Figure 19b). The design was based on work by Liv and Jordan[52] and earlier analytical work by Garg[53]. The vertical, cylindrical storage tank had a height of twice the diameter to reduce the heat loss when the hottest water is located in the upper part of the tank. The total collector area was about 100 ft^2, and heated the water in the tank to as hot as 130^{o}F, with a collection efficiency of 50%. The pump consumed only 7 kilo-watt hours per month. Gupta and Garg[54] have reported a detailed computer simulation of solar water heater performance.

Solar water heating has been quite popular in Israel, and by 1965 over 100,000 units had been installed.[55] One reason is that until recently the cost of electricity and heating fuels has been high enough to make solar heating more economical. The first solar water heaters in Israel were sold with a three-year guarantee. This was soon raised to 5 years, and for a small additional cost could be extended to 8 years.

Malik [56] reported the results of tests of ten types of collectors with

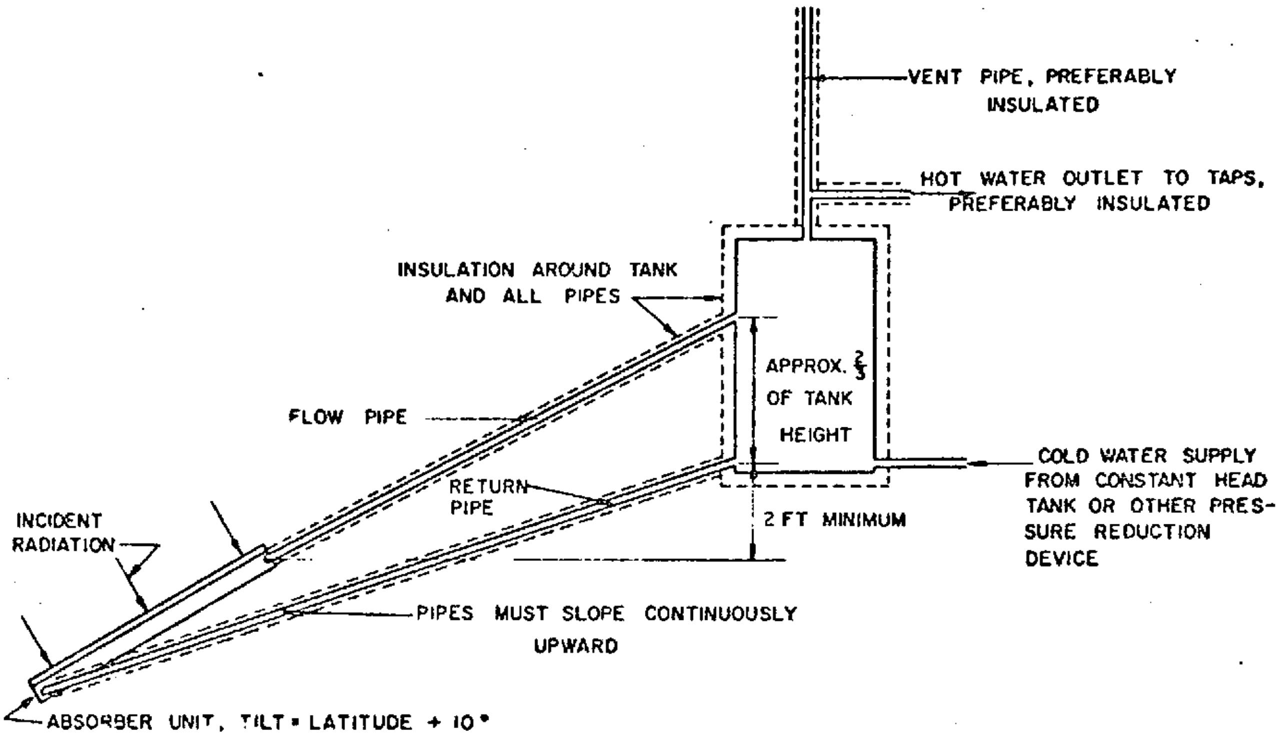


Figure 20. Natural Convection Solar Water Heater [56]

the natural convection water heater shown in figure 20. A small reverse flow occurs when the collector is cooler than the water in the tank, which has a certain advantage in the winter in that it prevents water from freezing in the collector. The tests measured the overall performance as affected by seasonal variations, type of transparent covering, insulation, height of storage tank and location of the point joining the flow pipe to the storage tank. The average efficiency was about 50% with a polyvinyl fluoride collector covering, and about 55% with glass. There was little effect on the efficiency of changes in insulation and seasonal variations.

In the United States today, solar water heating should probably be utilized with all new apartment and housing units in areas with mild winters.

In more northern climates where winter temperatures drop well below freezing, natural circulation systems such as shown in figure 20 and closed-loop systems such as indicated in figure 17 can be used. These systems now compete economically with alternative approaches, except in the northernmost parts of the country.

AIR CONDITIONING

Solar cooling is usually accomplished by using solar heat to operate a thermal absorption type refrigeration system. Daniels [57] described the basic principles of solar cooling as follows:

"The principles of absorption-desorption solar cooling are well established and fuel-operated refrigerators have long been on the market. In electrically operated refrigerators, a vapor such as ammonia is condensed to a liquid with a motor-driven pump, and the heat evolved is removed with circulating air or water at room temperature. The liquid is then vaporized in an insulated box and heat is removed by the vaporization to give the cooling effect. In solar refrigeration, the cycle is similar except that the pressure is built up by heating a concentrated solution of ammonia to give a high vapor pressure, instead of compressing the vapor mechanically. There are two connecting, gas-tight vessels, one of which contains liquid ammonia and the other a very concentrated solution of salt in liquid ammonia. The salt solution has a much lower vapor pressure, and the liquid ammonia vaporizes in its compartment, thereby cooling it, and dissolves in the salt solution contained in the other compartment. The system is regenerated by using focused solar radiation to raise the temperature of the salt solution to such a high temperature that the vapor pressure of ammonia in the solution exceeds the vapor pressure of the pure liquid ammonia in the second compartment. In this way, the operating cycle produces cooling by evaporating ammonia as it goes into the concentrated solution of salt, making it more dilute; and the solar regeneration drives out the ammonia from the diluted salt solution to produce pure ammonia and leaves a more concentrated solution.

A cycle has been studied in which a concentrated solution of lithium bromide absorbs water vapor and causes liquid water in another compartment to vaporize and produce a cooling effect. The lithium bromide solution is concentrated again by heating the diluted solution with solar radiation and the system is operated on a continuous basis. A laboratory was partly air conditioned by the sun for a while during these tests."

A continuously operating absorption air-conditioning system was built and tested in the early 1960's at the University of Florida [58]. Hot water was used to heat a high-concentration, ammonia-water solution (50 to 60% ammonia by weight) in a generator, driving the ammonia out of the solution. The ammonia vapor was then condensed and expanded through an adjustable expansion valve and entered the evaporator as a two-phase mixture. The liquid component evaporated, cooling the water circulating through tubes in the evaporator, and then reabsorbed into the water, and the ammonia solution was pumped back to the generator to repeat the cycle. Ten 4 foot by 10 foot flat-plate solar collectors provided the hot water to operate the air conditioner. The absorbing surfaces were tubed copper sheets painted flat black, placed in galvanized sheet-metal boxes with two inches of foam-glass insulation behind, and a single glass cover. The system was operated with heating water temperaturesranging from 140 to 212^{o}F. The maximum cooling effect was 3.7 tons, and steady operation was achieved with 2.4 tons of cooling.

Teagen [59] proposed a solar powered air conditioning unit driven by an organic Rankine cycle engine. Solar heat would be used to vaporize an organic fluid at a temperature between 160^{o}F and 280^{o}F to drive a Rankine cycle engine, which in turn drives the compressor of a vapor-compression air conditioning system. The coefficient of performance should compare favorably with absorption air conditioning systems, but at the present time none have been built.

Lof [60] compared the cost of solar heating, solar cooling, combined solar heating and cooling, oil or gas heating and cooling, and electric heating and cooling (Table 7) and concluded that, except for the northern-most part of the country, combined solar heating and cooling is cheaper than solar heating or cooling alone. Solar costs were based on $\$2/ft^2$ collectors, amortization over a 20 year life, 8% interest, 1970 prices, and an additional $1,000 capital cost for solar air conditioning over electric, gas or oil air conditioning. Water heating was included, and the water storage cost was taken to be $0.05/ lb water.

Table 7. Heating and Cooling Costs [60]

$ Per Million BTU

	Oil or Gas	Electric	Solar Heating	Solar Cooling	Solar Combined
Albuquerque	0.95	4.63	2.01	3.24	1.70
Miami	2.04	4.87	11.63	2.19	2.07
Charleston	1.03	4.22	3.34	3.50	2.47
Phoenix	0.85	5.07	2.86	2.05	1.71
Omaha	1.12	3.25	2.93	5.41	2.48
Boston	1.85	5.25	3.02	8.74	3.07
Santa Maria	1.52	4.28	1.57	14.60	2.45
Seattle	1.96	2.29	3.15	19.63	3.79

As is seen from Table 7, solar heating is very costly in Miami where not much heat is needed, and likewise solar air conditioning is not economical in northern climates where little air conditioning is needed. The primary reason that the combined system is usually cheaper than either alone is that it permits both summer and winter utilization of the solar collector, which is the most expensive part of the system. Thus, in most parts of the U.S., the economics favor combined solar heating and cooling, rather then either alone. Figure 21 illustrates such a combined system using a common collector, storage tank, auxiliary heater, and blower for both heating and air conditioning.

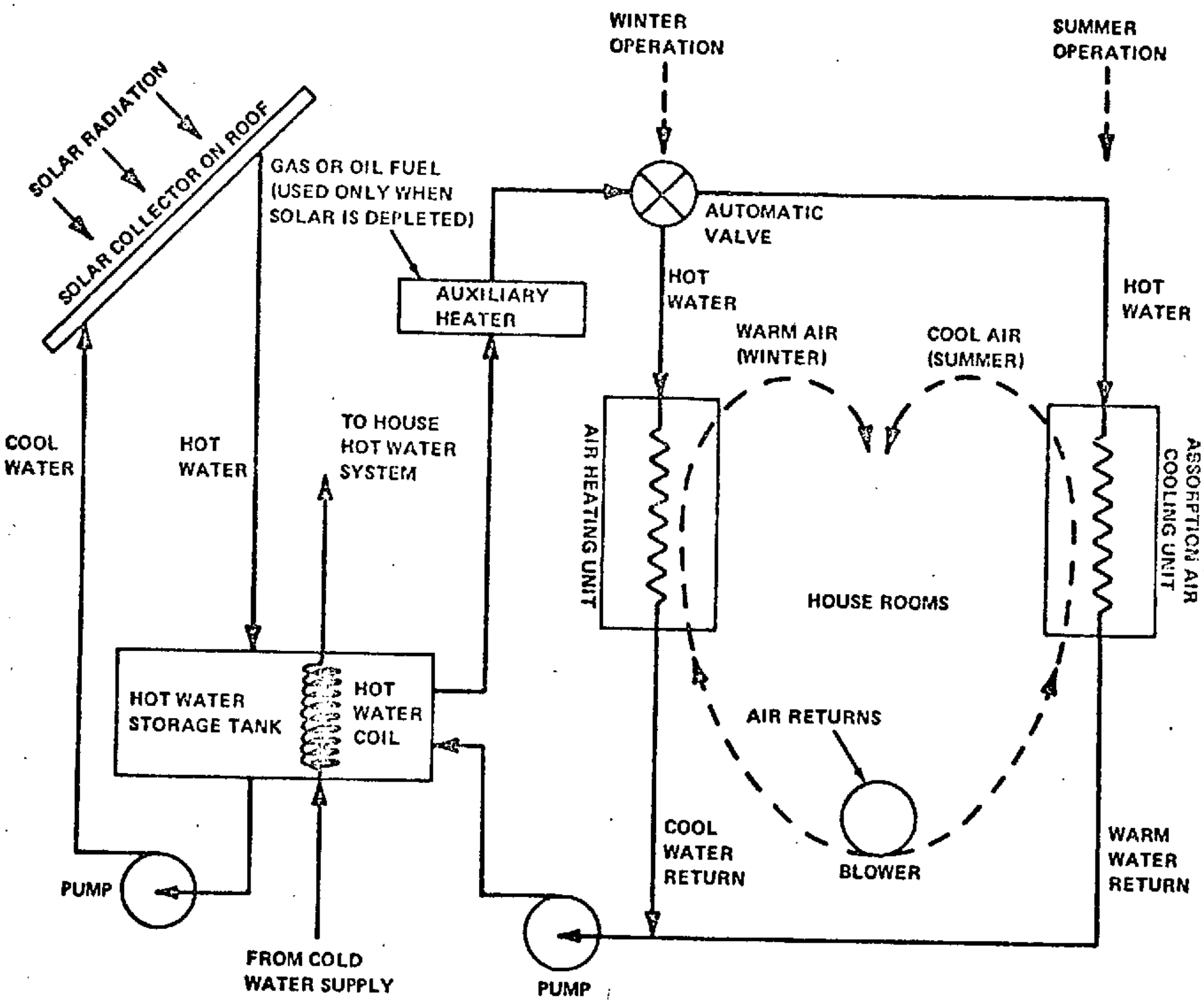


Figure 21. Combined Solar Heating and Cooling System.

ELECTRIC POWER GENERATION

A variety of approaches have been used for converting solar energy into electricity, including solar-thermal conversion, photovoltaic devices, and bio-conversion. Sunlight is an abundant, clean source of power, all that is required is the development of technology to economically convert this energy into electricity.

The NSF/NASA Solar Energy Panel [13] has identified the various possible steps leading from solar radiation to power delivered to the consumer (Figure 22). In this scheme plants, rivers, winds, ocean currents and ocean temperature gradiants are considered natural collectors of solar energy. Solar energy can also be collected directly as heat, or converted into electricity via the photoelectric effect. If collected as heat, the heat can be stored for use when the sun is not shining. The heat can be used to operate a power plant or to produce a chemical fuel, such as through the thermochemical production of hydrogen. The fuel can be stored, and used as needed to produce electric power, such as with the hydrogen-air fuel cell.

With so many possible approaches available for the production of electric power, the problem then is to choose that approach which is most cost-effective for a specific application. This is sometimes difficult since technology is advancing rapidly in most of these areas, and the comparative economics becomes uncertain. At present, the two technological approaches which offer the most promise are photovoltaic conversion with electrical storage, and solar-thermal conversion with heat storage for nighttime operation.

Solar-Thermal Power Generation

The two main approaches to solar-thermal power generation are the solar furnace approach, in which sunlight reflected from many differant locations is concentrated on a single heat exchanger, and the solar foam, with large numbers of linear reflectors focusing solar radiation on long pipes which collect the

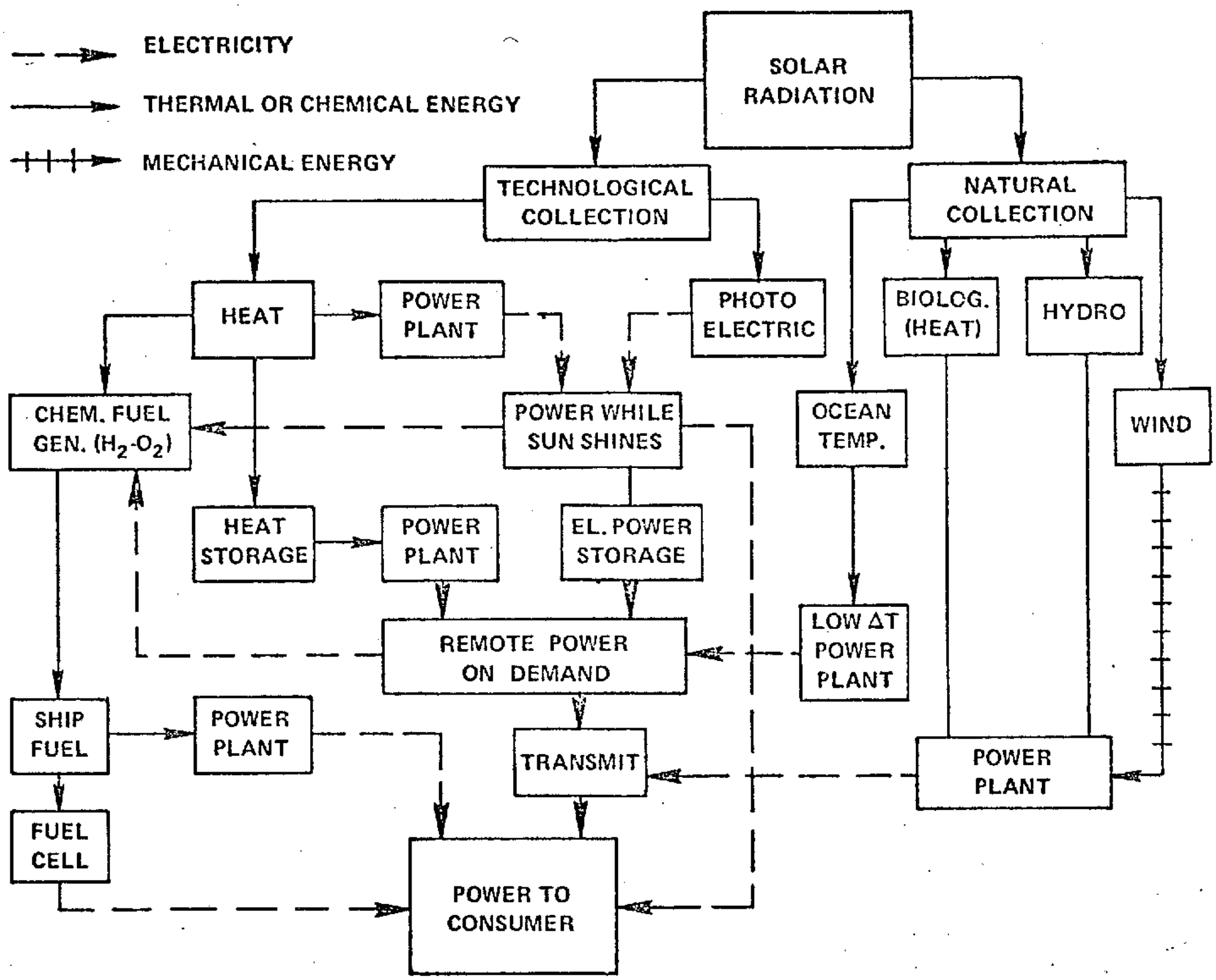


Figure 22. Possible Approaches for the Conversion of Sunlight into Electricity[13]

heat.

The tower concept (Figure 23) proposed by Lenitske[61] in 1949 is a good example of the solar furnace approach. A large number of flat mirrors covering a large area of land independently focus sunlight onto a boiler, which is mounted at the top of a tower located near the center of the field of mirrors to produce high temperature steam for driving a turbine. A 50 kilowatt plant

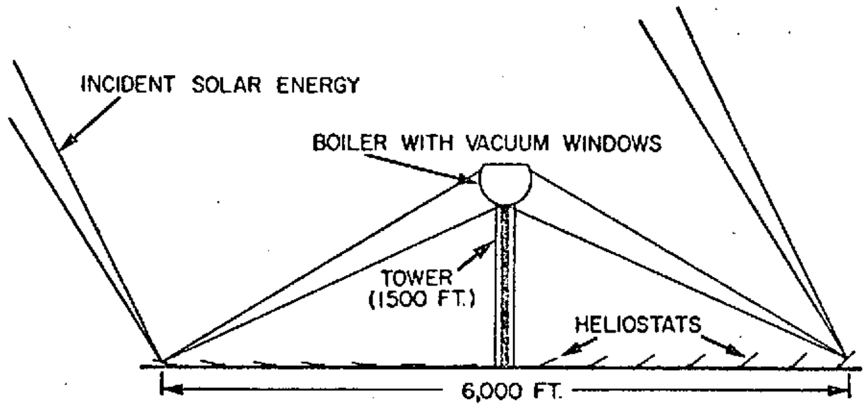


Figure 23. Tower Concept for Power Generation

has been built and operated in Italy [62]. An advantage of this system is that the separate mirrors and steering mechanisms can be inexpensively mass produced, and the smaller reflectors are less subject to high wind loadings than a single large steerable concentrator of the same total collector area.

A recent proposal by Hildebrant and Vant-Hull [63] involves using over a thousand 10 foot square mirrors covering a 6000 foot diameter circle of about one square mile area to reflect sunlight onto the boiler on top of a 1500-foot high tower (Figure 23). Each mirror would be steered separately by a heliostat as shown in figure 24. Hildebrant acknowledges that "Since the major expense of solar energy collection employing a solar furnace would be the heliostats, considerable research needs to be done in order to develop a heliostat which could be economically mass produced." The 150 foot diameter, 1500 foot high tower would cost about $15 million. The boiler could be made of steel and operate in the 1000°C range, and the solar image size at the boiler would be 31 feet in diameter. The outer boiler surface would be black and surrounded by an evacuated glass envelope. About 20% of the incident solar energy would be lost upon reflection by the mirrors, and another 6% lost by reflection from the boiler glass envelope. If 45% of the land area is covered with mirrors the boiler could collect 630 BTU/day per square foot of mirrors in the Southwest U.S. in the winter,

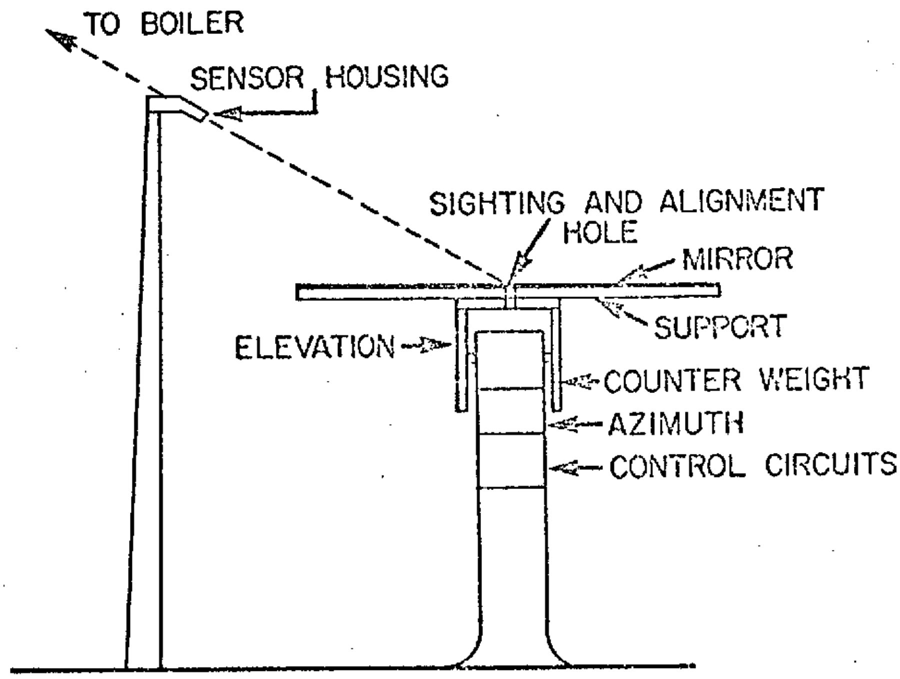


Figure 24. Heliostat System for Steering Mirrors

1320 BTU/ft^2 day in the spring and fall, and 1620 BTU/ft^2 day in the summer. The total cost of heat collected by this plant is estimated at $0.48 per MBTU [63], which is competitive with the cost of fossil fuels delivered in large quantities to a power plant. This cost estimate is based on a $2/ft^2 cost for the mirrors and heliostats and $15 million for the tower. The heliostats must aim the mirror with an accuracy of 0.2° in the presence of winds.

Trombe [64] has developed a megawatt solar furnace in France employing heliostats with 20 inch square flat glass mirrors and a fixed parabolic concentrator on the side of a nine-story building. The flat mirrors reflect sunlight toward the fixed parabolic concentrator, which focuses the sunlight. The heliostats and mirrors cost $21/ft^2. Walton [65] is preparing to use this facility for tests of boiler surfaces which might be used with the tower concept for electrical power generation. Major problem areas which must be investigated are 1) heat shock from the many thermal cycles which result from clouds passing in front of the sun and 2) investigation of the absorption - reflection - radiation characteristics of potential boiler surfaces operating at high temperatures and high heat fluxes.

"Solar foams" have been proposed using parabolic trough concentrators to focus sunlight onto a central pipe surrounded by an evacuated quartz envelope (Figure 6). Heat collected by a fluid flowing through the pipes could be stored at temperatures over 1000°F in a molten eutectic [66], and used as required to produce high enthalpy steam for electric power generation. Another approach is to store the heat in rocks, and extract the heat as required to generate steam on demand (Figure 25).

Russell [67] has proposed a central station electric power plant based on his fixed-mirror solar concentrator which produces a sharply focused line image regardless of the incident sun direction. The major advantage of the fixed mirror concentrator is its potential cost reduction as compared with other types of concentrators capable of providing heat at more than 1000°F.

In order for large scale solar-thermal electric power generation to become economically feasible, the cost of the collector must not exceed about one dollar per square foot [68]. However, concentrating solar collectors which must be steered to follow the sun cost more than $4/ft^2, and a major part of this cost is the steering mechanism and the mechanical structure which must withstand reasonable wind loadings. The fixed mirror concentrator, on the other hand, does not have to be steered and need not be self-supporting, so fabrication of these concentrators should be much cheaper then steerable reflectors. Since the point of focus always lies on the reference cylindrical surface, the heat exchanger pipe can be supported on arms that pivot at the center of the reference cylinder. This greatly simplifies the positioning of the heat exchanger.

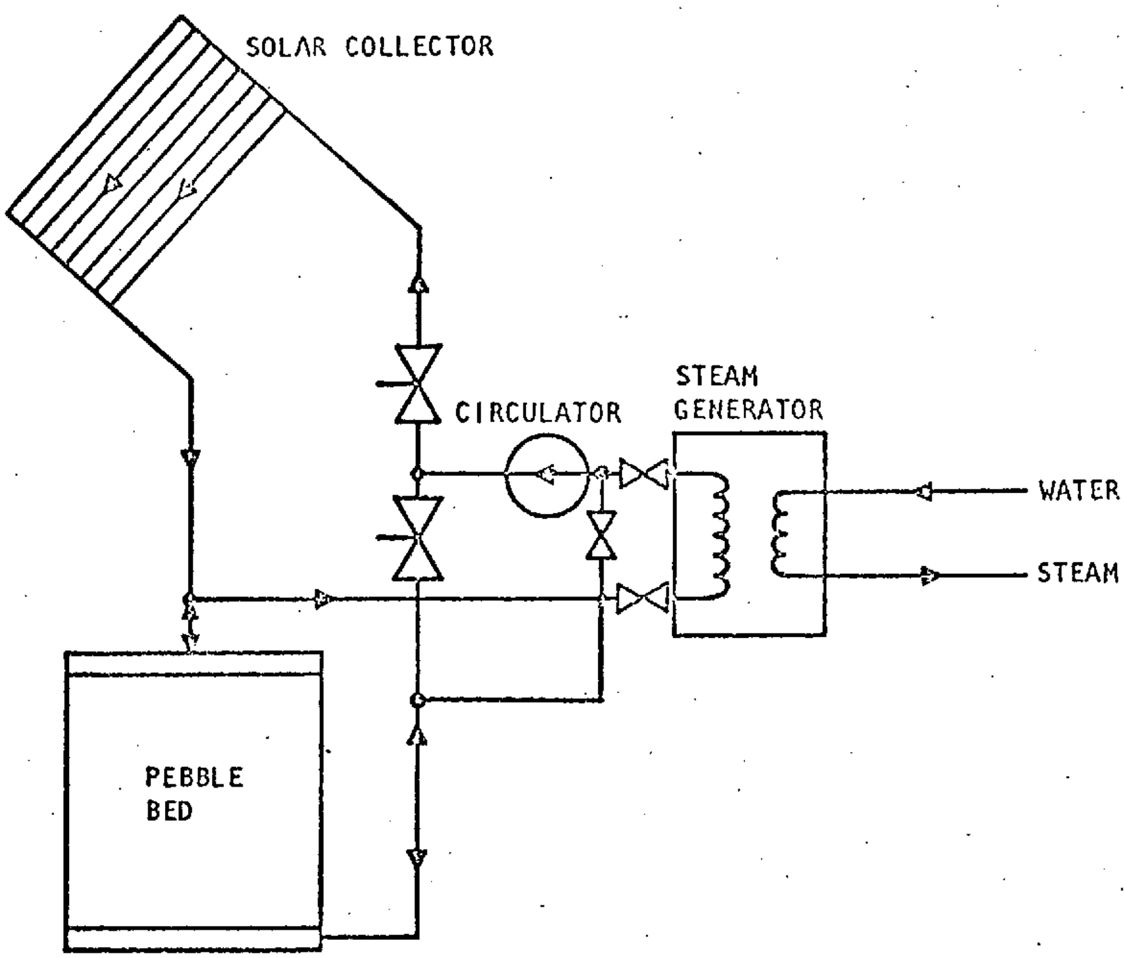


Figure 25. Flow Diagram for a Solar Thermal Power Plant [67]

Russell's proposed power plant for the Southern California desert would be arranged in modules (Figure 26) with 30 foot wide mirrors arranged in a 1500 by 1880 foot array, with a gravel tank for heat storage and the steam generator located in the center. Air at 100 psi is heated in the collecting pipes by the focused sunlight and flows through the pebble bed and/or the steam generator. Steam at 1000°F could be supplied from 9 of these modules to a centrally located turbogenerator of 162 MWe capacity. Figure 27 illustrates the fixed mirror concentrator array. Costs of power from this facility

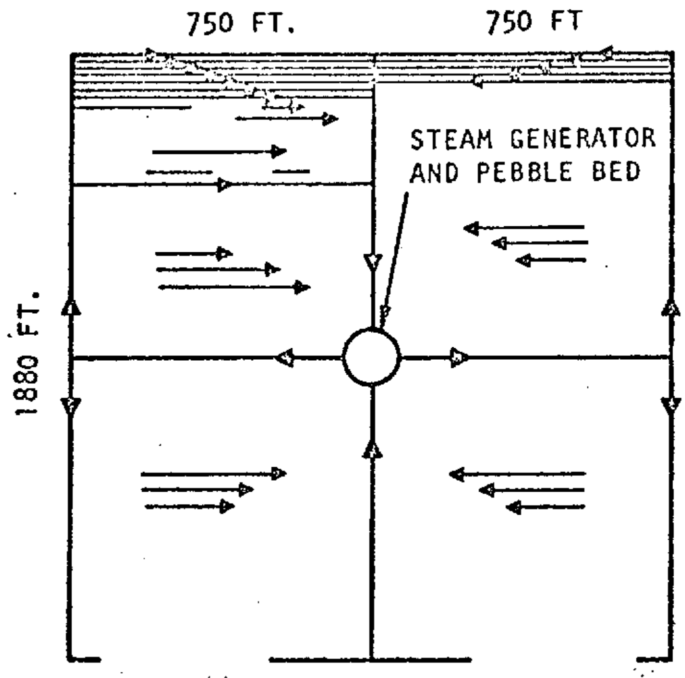


Figure 26. Module Of fixed MirrorPower Plant[67]

is estimated to be competative with alternative means of power generation. Land costs would be negligible since, even at $1000/acre, the land cost is only $0.023/ft^2. Desert land is even cheaper.

Meinel [69] has proposed a 1,000,000 MWe solar-thermal power plant covering about 13,000 square miles of desert extending from the upper regions of the Gulf of California as far north as Nevada (Figure 28). The plant would use waste heat to produce 50 billion gallons of water each day, enough to meet the needs of 120,000,000 people. The proposed plant would use a circulating liquid metal (sodium or NaK) to extract heat from a solar foam and store it in a phase-change salt or eutectic mixture at temperatures in excess of 1000°F. Power would be produced by a high pressure steam turbine-generator, and the low pressure steam from the turbine used to distill water. The total cost of solar heat collected by this plant is estimated at $0.50 per KW hour.

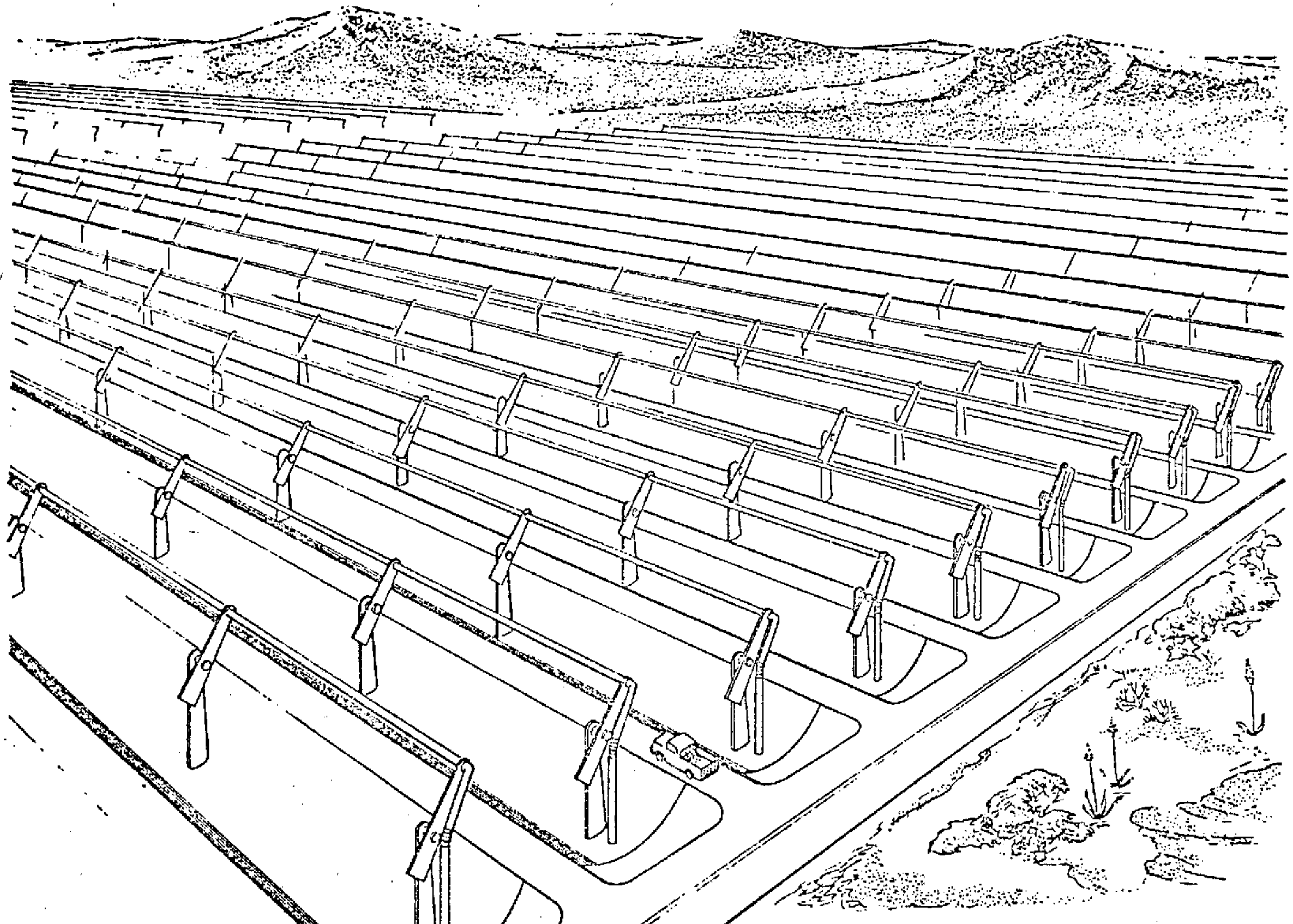


Figure 27. Artist's concept of fixed-mirror solar concentrators showing the mirrors and the tracking heat absorber pipes [67]

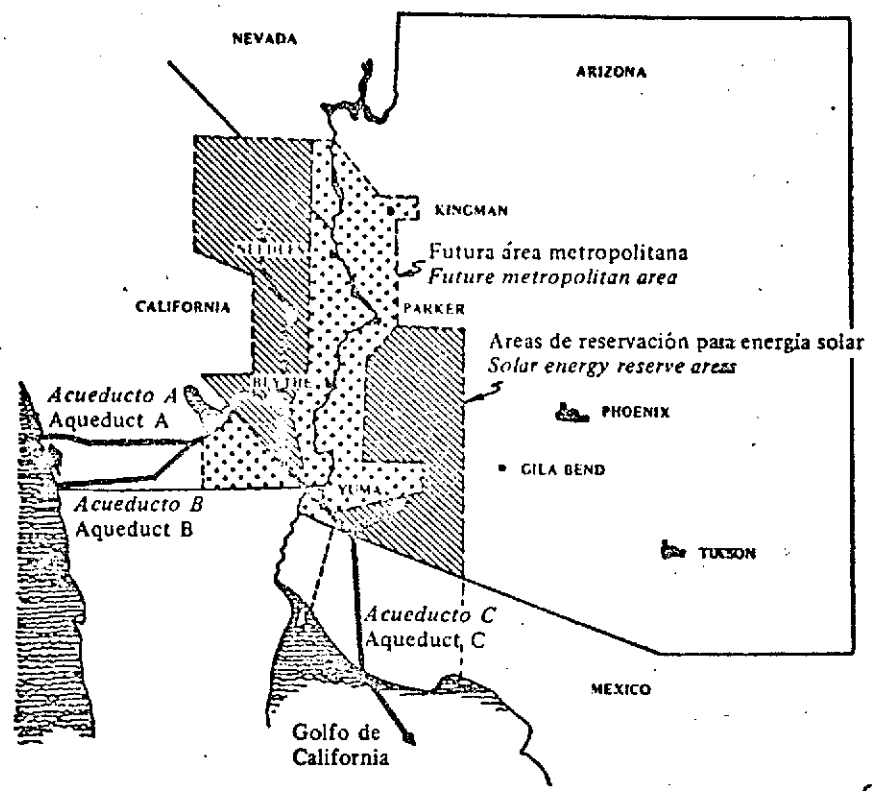


Figure 28. Proposed Location of National Solar Energy Reserve[69]

Photovoltaic Power Generation

Solar cells offer a potentially attractive means for the direct conversion of sunlight into electricity with high reliability and low maintainence as compared with solar-thermal systems. The disadvantages at present are the high cost of about $25/watt [70] and the difficulty of storing large amounts of electricity for later use as compared with the relative ease of storing heat for later use. The cost of solar cells is expected to be considerably reduced when cells are manufactured in large quantities using new production techniques for obtaining ribbons or sheets of single crystal silicon. At present large crystals of silicon or other semiconducting material are grown and then sliced into thin cells; new techniques for producing the thin slices directly use edge defined film growth [71], dendritic growth [72], rolled silicon [73], or sheets of cast silicon which are recrystallized through heated or molten zones [74]. Silicon itself is very cheap since it is the second most abundent element in the earth's crust, and is produced in the U.S. at an annual rate of 66,000 tons at a cost of

\$600/ton, so when the most suitable of these mass manufacturing techniques is utilized the cost of solar cell arrays should be reduced to \$1/watt or less, making them useful for the large scale generation of electric power[71, 75].

Four companies which manufacture solar cells are Heliotech, Centralab, Solar Power Corporation (Exxon), and Sharp. Solar Power Corporation[76] sells a small solar power module that produces 1.5 watts at a solar intensity of 100 mW/cm^2. The current and power output characteristics of these solar cells (typical of solar cells in general) are given by figure 29. Standard conditions are $0^{\circ}C$ and 1000 W/m^2 insolation, typical conditions are $25^{\circ}C$ and 800 W/m^2

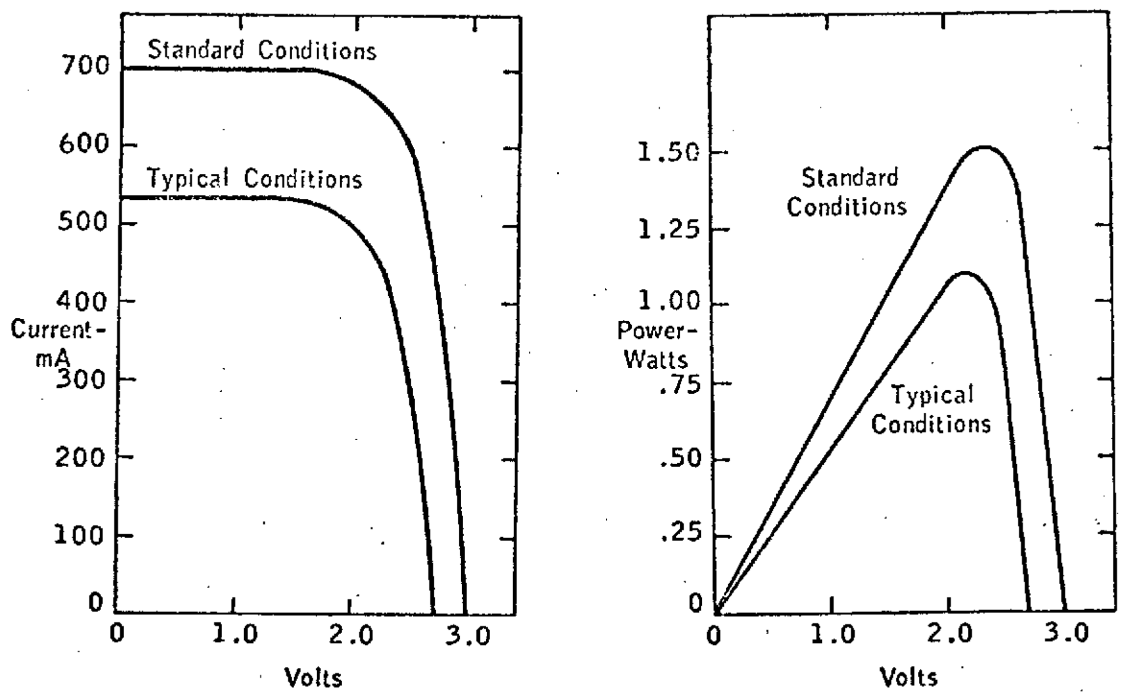


Fig. 29. Operating Parameters of Solar Cells[76]

are $0^{\circ}C$ and 1000 W/m^2 insolation, typical conditions are $25^{\circ}C$ and 800 W/m^2

insolation. The solar array module consists of five 2.17 inch diameter silicon solar cells attached to a 13 1/2 inch by 2.9 inch panel and is usually used to change storage batteries to provide a continuous supply of power in remote locations. Tests in Arizona showed no degradation in output over a six month period. One power system being used at present to power navigational lights consists of 80 of these modules, 28 100 amp-hr 12 volt storage batteries, and the electronic control circuit. This power supply is cheaper to use than the alternatives; the Coast Guard saves about $3 million per year by using solar powered buoys [77]. The cost reduction is mainly due to the smaller number of trips out to the buoys for servicing. Wires are used to keep seagulls off, but nothing is done about snow. NASA's experience testing solar cell arrays in Cleveland has shown no significant reduction in power due to dirt or dust accumulation and little problem with snow [20].

Rink and Hewitt [78] have studied the possibility of using a large solar cell array to supply the electric power needs of the western United States in 1990, assuming that solar cells can be mass produced at $1/watt. An array covering 192 square miles, coupled with pumped storage, would supply the 14,300 MWe needed by Arizona in 1990 for about $58 billion and an array covering 2200 square miles (44 miles by 50 miles) would supply 40% of the electrical power needs of the eleven western states for a capital cost of around $673 billion. Since these costs are far in excess of alternative means of power generation, it appears that even at $1/watt solar cells will be too expensive for central station power generation. Wolf [79] has concluded that the cost of solar cells must be reduced to about $0.20 per watt before solar cell arrays become practical for central station power generation.

The cost of generating electric power with solar cells can be reduced by using concentrators to focus sunlight onto the cell. One simple type of concentrator is the reflecting cone [26, 80] (Figure 30). Without external cooling concentration ratios of up to five can be used without seriously reducing the

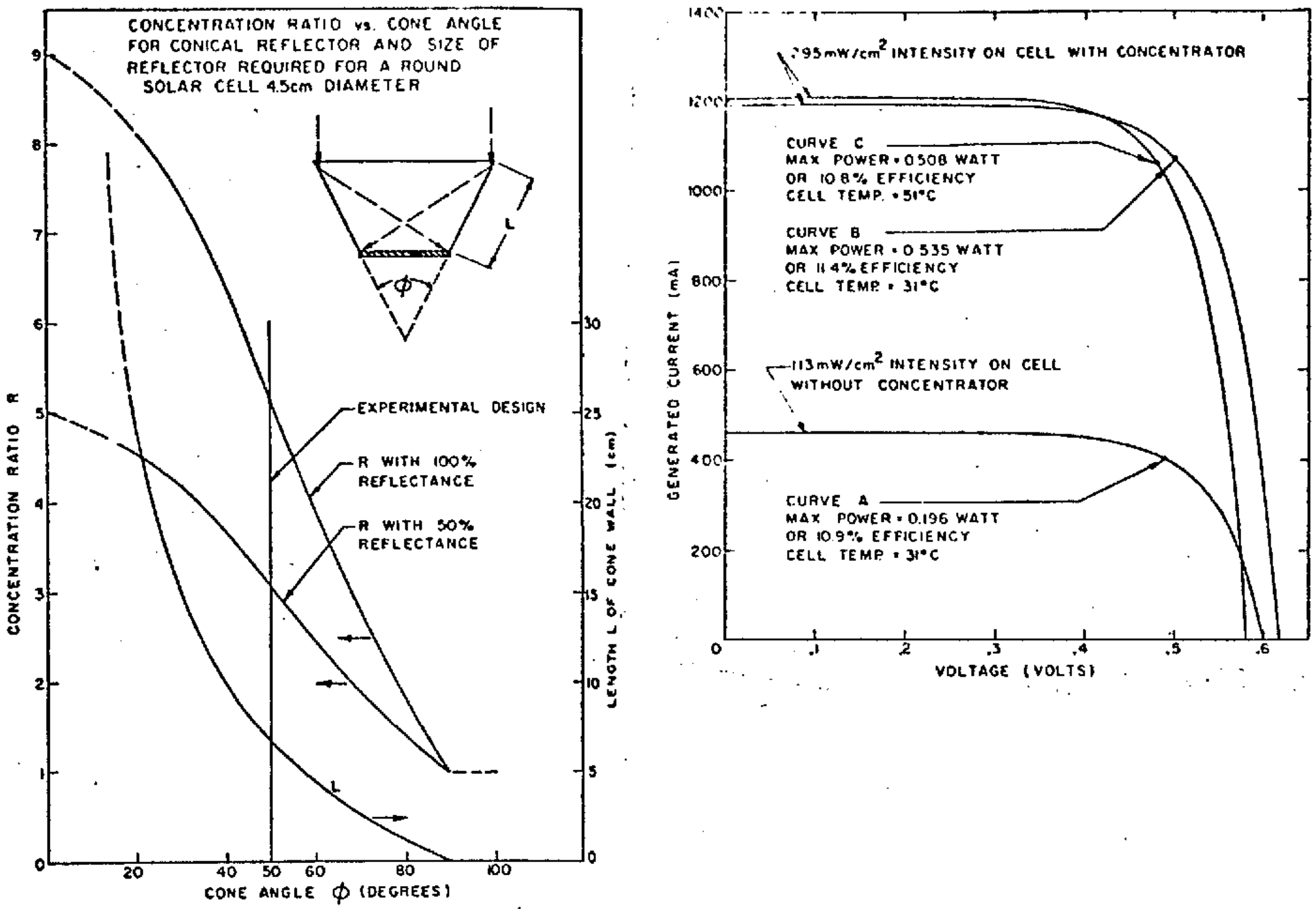


Figure 30. Concentration Ratio of Cone Reflector and Effect on Solar Cell Performance

cell performance due to cell heating. Higher concentration ratios are possible with external cooling. Solar cell arrays with concentrators must be steered to follow the sun ; in the case of the conical concentrator tested by Ralph[80] the output is reduced below that with no concentrator if the angle of incidence is less than 60 degrees, and at angles of less than 45 degrees the output is negligible.

Another related design is the channel concentrator consisting of two flat reflecting surfaces at an angle of 30^{o} placed on both sides of a line of solar cells. The theoretical maximum concentration ratio is 3; an actual concentration ratio of 2.25 was achieved with a channel concentrator array built by Ralph[70]. His array used 2 in by 2 in silicon solar cells at the base of the V channel. Five channels with 30 cells each formed a 4.75 lb., 1 foot by 2 foot array producing 12 watts at 12 volts.

With external cooling, silicon solar cell outputs can be increased by more than 100 with concentrating systems [81]. Using experimental data[82] for cells operating with solar fluxes between 14 and 28 watts/cm^2, Beckman[83], et.al., designed a system to produce 50 watts of electrical power from 36 square centimeters of cell area by using a 5 1/2 foot parabolic concentrator to provide a solar flux of 28 watts/cm^2. The cells would be water cooled to maintain their temperature at 200^{o}F. Five watts would be required to pump the water. Lidorenko[30], et.al., built and tested a 250 watt electric power plant using a concentrator consisting of 26 plane mirror facets forming an approximate parabolic cylinder. The concentrator increased the power output a factor of 5.2 over the power output with no concentrator, the solar cells were water cooled, and the overall plant efficiency was 2.7%[84]. Another plant was developed by the same group using channel concentrators with a concentration ratio of 2.5, and not requiring water cooling. These plants were developed "to provide power for water pumps in the grazing areas of the southern regions of the U.S.S.R.". According to <u>Moscow News</u>[85], one of their solar cell plants "has been installed at the Bakharden state livestock-breeding farm situated in the Kara-Kum Desert, Turkmenia. Its output equals about 400 watts-enough to lift from a depth of 20 meters, a sufficient amount of water to water 2,000 sheep".

TOTAL ENERGY SYSTEMS

The feasibility of using solar energy to provide for all of the various energy needs of a home, business, or community requires either the development of inexpensive solar cells or an economical means of collecting solar heat at high temperatures and converting it to electric power. Photovoltaic cells can be combined with a flat plate collector (Figure 5) so that the radiant energy not converted into electric power is collected as heat and used to supply hot water, space heating, absorption refrigeration, and air conditioning. Figure 31 illustrates a solar cell flat plate collector which would permit utilization of up to 60% of the available solar energy. Collectors such as this mounted on vertical walls and/or part of the roof of a house or apartment building can supply all the various types of energy needs of the building. Figure 32 is a schematic showing the energy flows for a residential solar energy system using solar cell flat plate collectors. This type of system is perhaps the ultimate in residential solar energy utilization, since both heat and electric power are produced without any moving parts, except for the pump or blower circulating coolant through the collector.

Advantages of this type of solar electric-thermal total energy system were listed by the NSF/NASA Solar Energy Panel[13] as 1) the collector uses the same land area as occupied by the building, and thus there is minimal effect on the environment through use of land presently being used for other purposes. 2) About three times the present average household consumption of eletric power can be collected from average-size family residences, even in the

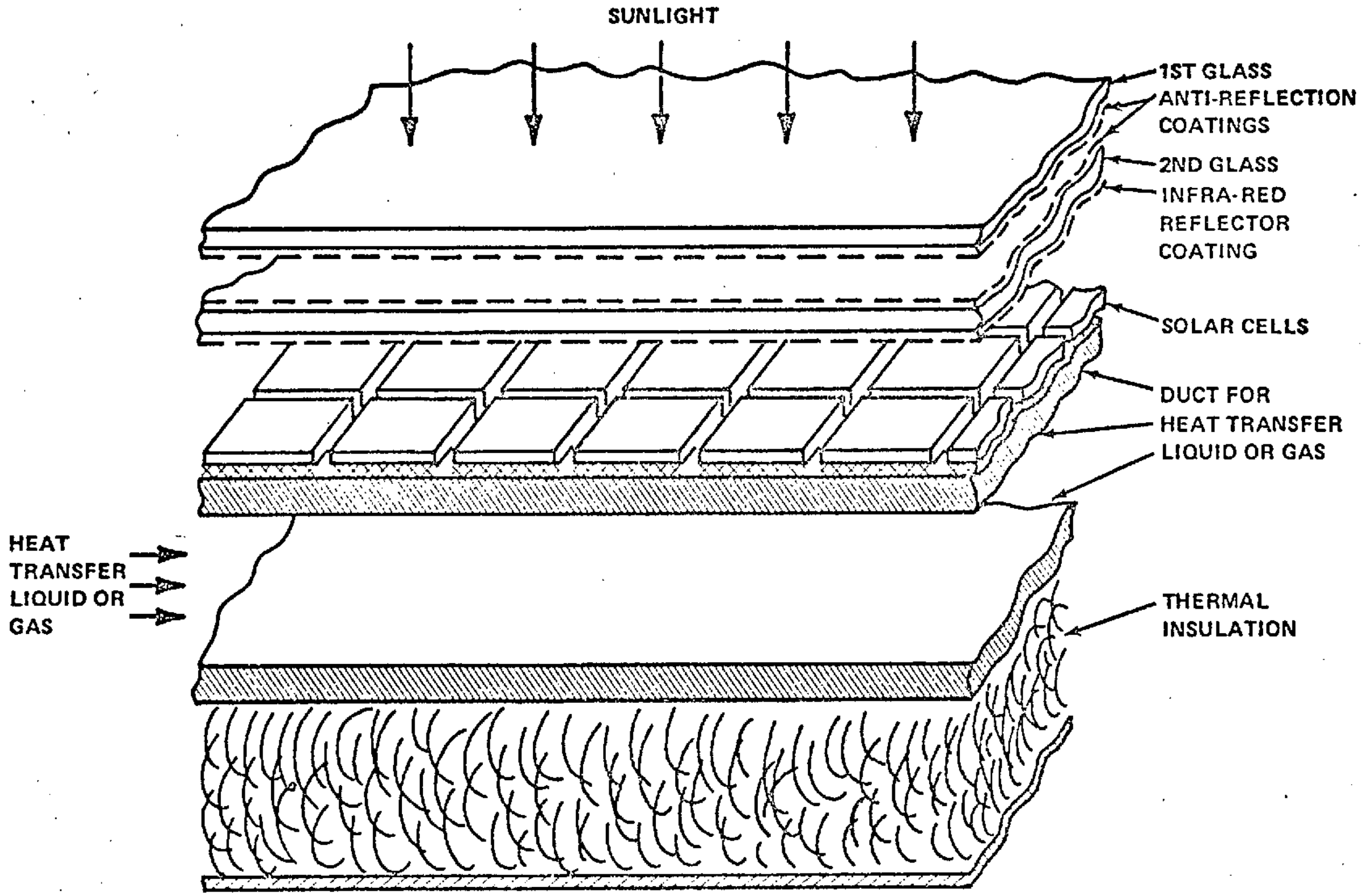


Figure 31. Flat Plate Collector with Solar Cells[13]

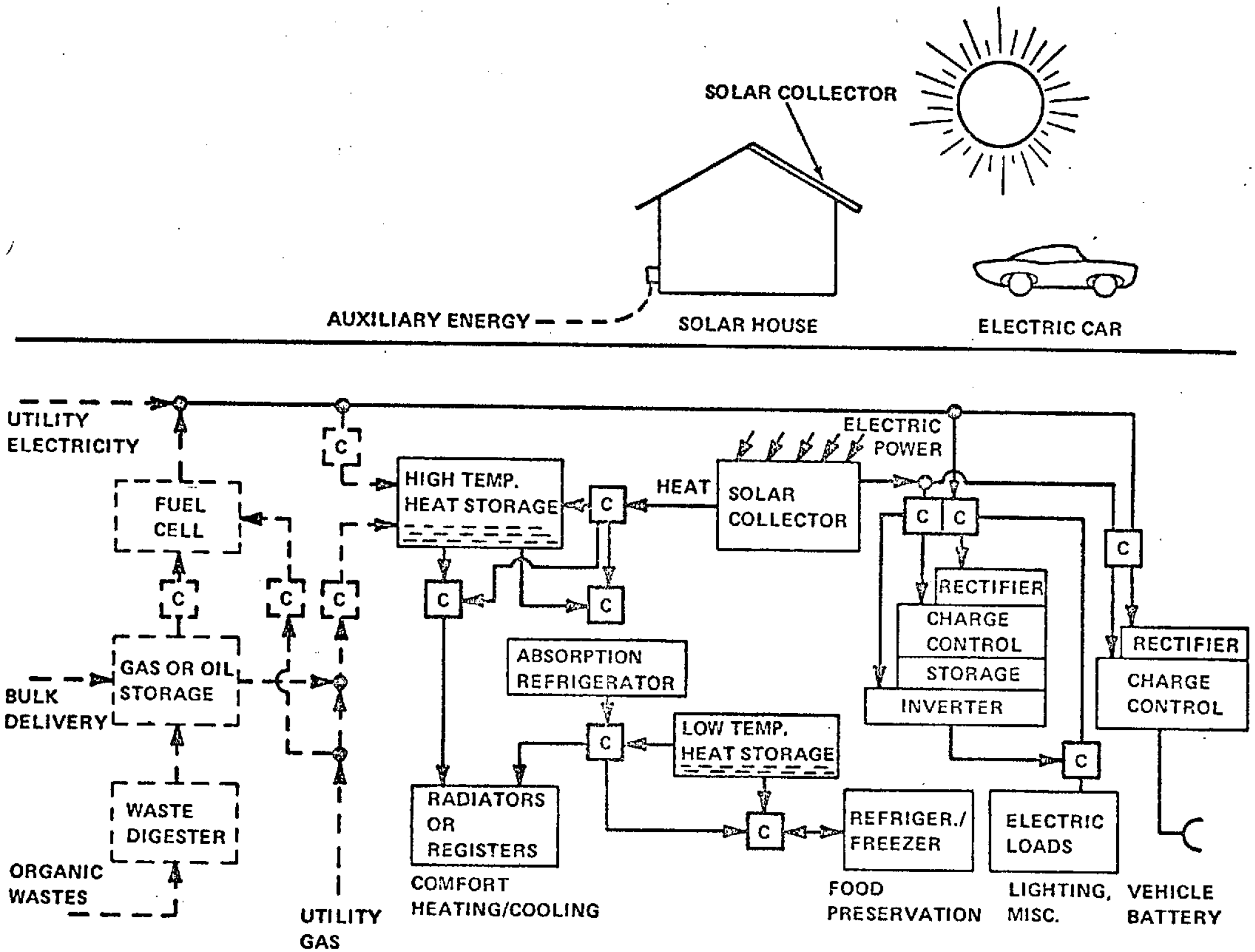


Figure 32. Schematic of a Solar Total Energy System for a Building.

northeastern U. S. This surplus energy could be used for charging an electric automobile. 3) The system is invulnerable to breakdowns in central energy generation stations or transmission systems. 4) The small size of the individual unit makes prototype testing and demonstration relatively inexpensive, and will help to attract consumer oriented industries.

Farber[86] has reported work at the University of Florida on solar water heaters, solar air heaters, a solar still, a five ton solar air conditioner, a solar refrigerator, several solar ovens, a solar sewage digester, solar cell arrays, several types of solar powered hot air engines, solar water pumps, a "solar-electric" car, and a solar house. The solar house, occupied by a graduate student and his wife, uses solar energy for space heating, water heating, swimming pool heating, electricity, and recycling of liquid wastes with the solar still. A 1/3 horsepower hot air engine operating from a 5 foot parabolic concentrator drives a d-c generator to charge the solar-electric automobile to provide pollutionless transportation from the solar house.[87] Thus it has been shown that it is technologically possible to use solar energy to provide all residential energy needs.

If inexpensive solar cells are manufactured, then the major remaining obstacle to the development of total energy systems is the problem of storing the electricity. Backus[88] has proposed a residential solar-cell electric power plant with hydrogen storage. Excess electric power generated during the day is used to electrolyze water to produce hydrogen and oxygen gas, which is compressed into storage tanks, and used in the evening with a hydrogen-oxygen fuel cell. This system is attractive in the long run, but too expensive at present for residential use. Another possible energy storage medium is the flywheel. Rabenhorst[89] has been studying a new type of safe flywheel with an energy storage capacity of 30 watt-hours per pound. Excess electric power generated during the day is used to increase the rotational velocity of the flywheel, and in the evening the energy of the flywheel is used to generate electric power. Lead-acid batteries could be used, but as noted by Loferski[90] "if lead-acid batteries were supposed to store a substantial fraction of all the electrical energy produced in the United States, it is questionable whether enough lead would be available". Other electrochemical systems, however, might be possible, but more research needs to be done.

The other approach to developing a total energy system, not involving solar cells, is to collect the heat at a high temperature using a dynamic conversion system to produce electric power, and use the waste heat for space heating and cooling. Pope[91] et. al, have analyzed four different types of total energy systems using concentrating collectors, high temperature heat storage, and a derated turbine,where the exhaust energy is used for heating and air conditioning. Another system with a flat plate collector driving an organic turbine generator was rejected as not being economically competitive with focused concentrator systems. The analysis used data from Schimmel[92] and Pope's[93] focused collector analyses to calculate the performance and economics of each proposed system for Alburquerque, N.M. One day in four was assumed cloudy and the direct insolation taken to be 80% of the total. The cost of the residential solar energy systems were compared with a "normal" system supplying equal energy demands with utility electric power, and natural gas for space heating, air conditioning, and water heating. The results of these calculations indicat that solar total energy plants with high temperature collection and three levels of heat storage would be economically competitive with the "normal" system when the wholesale fuel cost reaches $0.90/MBTU.

Large users of energy such as apartment complexes, shopping centers, and industries can take advantage of solar-thermal total energy plants ranging in size from 0.2 to 20 megawatts. As of 1972 there were about 550 total energy plants in this size range in operation in the United States[94]. The more recently installed plants have averaged over 5 megawatts in capacity. The electrical storage problems for all types of total energy plants can be reduced considerably if the electric utility company owns and maintains these systems, and allows the excess power generated during the day to be fed back into the utility power grid. The electric power company could then give a credit on the electric bill for power supplied by the customer. The major technical difficulty with this scheme is the phase-matching problem encountered when many different AC sources supply a common grid.

INDUSTRIAL AND AGRICULTURAL APPLICATIONS

The parabolic concentrator has provided an economical means of generating very high temperatures for small scale industrial applications and for research purposes, and solar heat at lower temperatures has been used for both industrial and agricultural drying operations. These represent two of the more promising commercial uses of solar energy.

Solar Furnaces

Trombe [64] developed a megawatt furnace in Montlouis France in the 1950's using heliostats to direct sunlight toward a large parabolic concentrator. Sakurai [95], et.al., built a similar 70 kilowatt furnace in Japan using a 10 meter diameter parabolic concentrator (Figure 33). Another furnace of the heliostat type in Nantick, Massachusetts uses a spherical concentrator.

The Japanese furnace began operation in 1963 and produces temperatures in excess of 3400°C, the melting temperature of tungsten. Refactory bricks have been melted "even in feeble sunlight." The furnace is used for studies of high temperature materials properties and some manufacturing. For example, alumina when melted in a graphite cylinder assumes a spherical shape because of its large surface tension. Turning the cylinder properly results in the formation of a fused alumina crucible which has much more desirable properties than a sintered one. Tungsten melted in an inert gas does not form a carbide even though the melting occurs on a graphite surface. Front surface aluminized mirrors used for the furnace showed a reduction in reflectivity from about 95% to 85% over a five year period. At the present time all the mirrors are aluminized once each year.

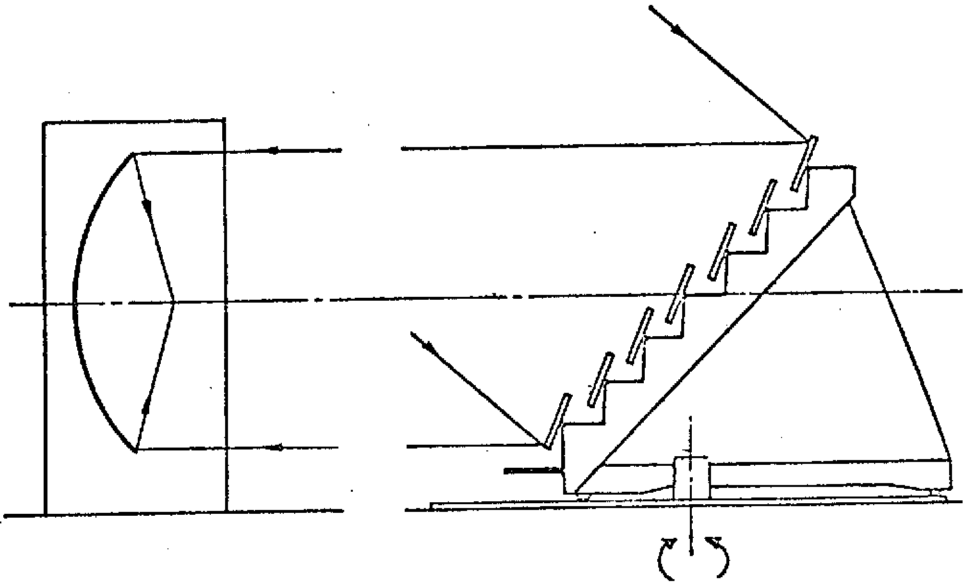


Figure 33. Optical System for a Solar Furnace.

A solar furnace in the Soviet Union "melts refractory materials at a temperature of up to 3,500°C, hot enough to liquify tungsten." [85] It is used for producing high purity refractories.

Air Heaters

Solar air heaters have a great potential for improving agriculturial drying operations around the world. As noted by Akyurt, [96] "A large portion of the world's supply of dried fruits and vegetables continues to be sun dried in the open under primitive conditions. Being unprotected from unexpected rains, windborne dirt and dust, and from infestation by insects, rodents and other animals, the quality is seriously degraded, sometimes beyond edibility. In an increasingly hungering world, practical ways of cheaply and sanitarily preserving foods would be welcome. Solar dehydration has not been fully dealt with by those concerned with solar research."

"Various investigators have experimented with two basic methods of dehydration. In the first method the necessary heat is supplied by directly exposing the material to solar radiation. Aside from its inherent simplicity, this process also enhances the proper color development of greenish fruits by allowing, during dehydration, the decomposition of residual chlorophyll in the tissue under direct solar radiation. The major drawbacks are the possible damage due to overheating, and relatively slow drying rates resulting from poor vapor removal in cabinet driers.

The second method is to heat the foodstuff by circulating preheated air. Since the drying material is not subjected to direct sunshine, caramelization and heat damage do not occur. A further advantage is that the circulating air entrains with it the emerging water vapor, thus accelerating drying. On the other hand, products of inferior appearance may result if immature fruit is dehydrated, since shading prevents the breaking down of chlorophyll."

Akyurt used a square meter area of steel chips beneath a glass cover to absorb solar radiation, and passedair to be heated through the chips. (Figure 34) Steel chips are cheap, have a high heat transfer area per unit volume and excellent turbulance geometries, and an absorptivity of 0.97. Several agricultural products were dried and compared with an open air sun-dried control group. Peppers dried in the solar dryer "possessed attractive bright colors as opposed to the brownish color of the slower drying control batch, which was sun-dried in the open."

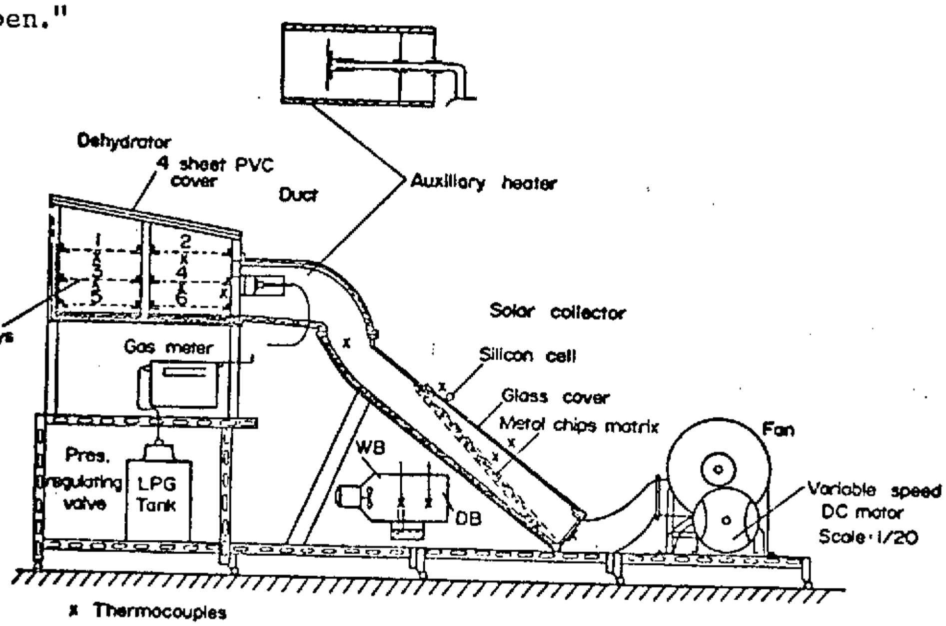


Figure 34. Solar Air Heater [96]

Similarly, "In the dehydration of sultana seedless grapes, the sun dried control sample was rained upon, and hence assumed a dark color. Soon afterwards it was attacked by birds whereupon its weighings had to be terminated. Raisins in the dehydrator possessed a golden color and were dried in spite of continuous rainy weather."

Close [42] has described a variety of types of solar heaters for use in crop drying, space heating, and for regenerating dehumidfying agents. These various types of heaters provide air at 100°F above ambient with collection efficiencies of 50% or more. The heat transfer processes in air heaters are quite differant from those in flat plate collectors which heat water. In the water-cooled collector, heat absorbed is transferred to the water tubes by conduction, so the absorber plate must have a high thermal conductivity. In an air heater the air can be in contact with the whole absorbing surface, so the thermal conductivity of the absorbing surface is of little importance. This makes solar collectors for heating air inherently cheaper than solar collectors for heating water. According to Close, "The main factors determining the efficiency of heat collection of a solar air heater operating at a given air inlet temperature are:

1 Heater configuration; that is the aspect ratio of the duct and the length of duct through which the air passes.

2 Air-mass flow through heater.

3 Spectral reflectance-transmittance properties of the absorber cover.

4 Spectral reflectance properties of the absorber plate.

5 Stagnant air, natural-convection barriers between the absorber plate and ambient air.

6 Heat transfer coefficient between the absorber plate and the air stream.

7 Insulation at the absorber base.

8 Insolation."

Close showed that V-corrugation of the absorber plate considerably improved the performance over that of collectors with flat absorbing surfaces. Spectrally selective coatings also improved profermance. Some of his air heaters of simple construction employing cheap materials were shown to be capable of supplying air at temperatures above 150°F with good efficiency. For crop drying only air temperatures below 180°F are needed.

One study [43] of flat plate air heaters with two glass covers showed that if the air is passed between the two glass panes before passing through the blackened metal collector (two pass) the outer glass temperature is reduced 4°F to 10°F, the collection efficiency increases 10% to 15%, and the temperature rise of the air is increased as much as 20%. Thus, it appears an attractive non-concentrating air heater design would use the two pass configuration and a V-corrugated absorber with spectricly selective coating.

Bevill [97] described tests of air heaters with an absorber consisting of 96 parallel specularly reflecting aluminum fins 6.35 cm high, 0.635 cm apart, and 61 cm long. A single 0.317 cm glass coverplate was placed over the absorber, and air pumped between the fins. The collectors measured 61 cm by 61 cm. The collector with specularly reflecting fins was shown to be about 15% more efficient than an identical collector with diffuse fins. Solar air heaters using hot water from water-cooled flat plate collectors have also been studied[98].

The use of concentrators to produce higher air temperatures for industrial operations, such as the 250° to 500°F needed by textile mills, has received little attention so far. Russell's [67] fixed mirror concentrator, (Figure 27) for example, could be used (as he has proposed) to heat air to high temperatures, and this heat can be inexpensively stored in rocks (Figure 25,26). But instead of using the hot air to generate steam for electric power generation, the air could be used directly for textile drying, and other industrial operations requiring hot air at temperatures up to 1000°F. At $\$4/ft^2$ for the heat supply system, the heat cost is about \$2.00/MBTU, less than many textile mills pay for the propane they are now using.

Solar stills are receiving increasing worldwide use for the production of drinking water from salty or polluted water. A still at the University of Florida [86] is used to reclaim drinking water from household liquid wastes. According to Hay [99] "solar stills remain the cheapest means for desalting quantities of less than 50,000 gal of saline water per day in areas of reasonable sunshine," and production costs are currently about \$3.50 per thousand gallons.

A solar still is typically a transparent plastic tent or glass enclosure containing a shallow pan of saline water with a black bottom. Sunlight heats the water in the pan, causing it to evaporate and recondense on the underside of the sloping plastic or glass and run down into collecting troughs along the inside lower edges of the transparent cover. Morse [100] calculated the performance of solar stills under various conditions of ambient temperature and insolation, and his results showed close agreement with data from a 4500 ft^2 solar still located at Muresk in Western Australia (Figure 35).

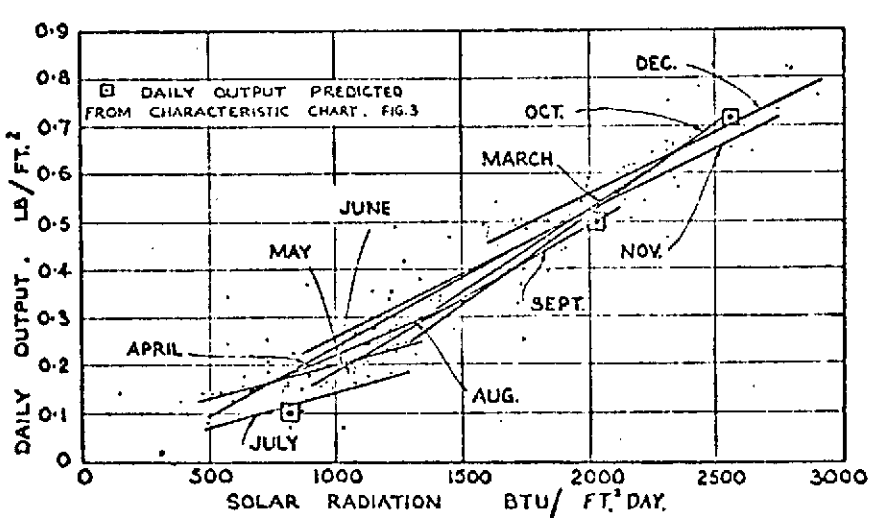


Figure 35. Daily Output of a Solar Still vs. Daily Insolation

The daily output rose from about 0.1 lb/ft^2 (450 lbs. total) of water per day in the winter (July) to about 0.8 lb/ft^2 (3600 lbs. total) of water per day in the summer (December), so the range of production for this still is from 0.012 gallons to 0.1 gallons per day per square foot of collector. Similarly, a large 23,300 ft^2 solar still [101] on the island of Saint Vincent in the West Indes provides the most economical source of fresh water (other than rainwater), since underground natural sources are not available and the cost of shipping water to the island is high. The average daily output of the plant is about 0.05 $gallons/ft^2$ of collector, or more than 1000 gallons per day for the plant. Four mil polyvinyl fluoride film is used as the transparent cover.

Hay [102] has reported the design of a solar still to be mounted on rooftops (Figure 36). An advantage of this approach is that the cost of the solar

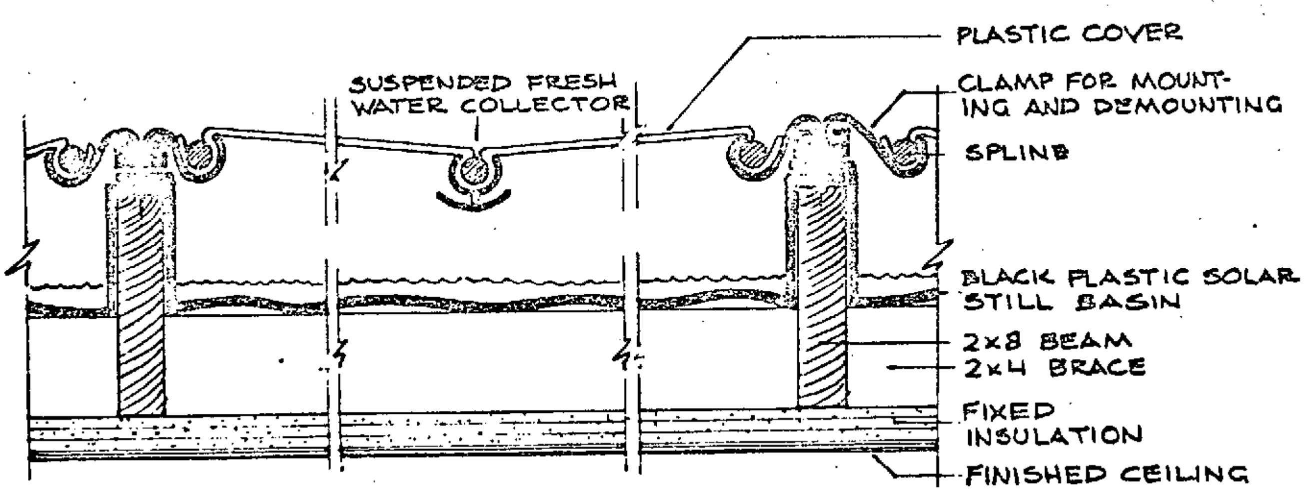


Figure 36. Plastic Rooftop Solar Still[99].

still is partially offset by the savings in ordinary roof costs, since the still replaces the roof. Also, the still is not occupying land area that could be put to other uses. Since solar collectors for space heating and cooling require only about half the roof area, the rest of the roof could be a still to provide fresh water. Shallow depths of saline water are used for maximum yield, so unlike the roof pond, the solar still would add little to the weight of the roof. According to Hay [99] "Several still designs are available with costs approximating those of conventional roofs." The stills use 4 mil polyvinyl fluoride film, treated on the underside for wettability, which should have at least a 5 year life. The inherent safety hazards of glass restrict its extensive use on roofs in densely populated areas, and breakage could cause puncture of the watertight lines with subsequent flooding of the room beneath. With proper design, replacement of the PVC cover every 5 years should be a simple matter. Plastic pipes and fittings would be used to reduce cost and weight.

The still in figure 36 uses a rigid basin of molded resin supported directly on the 2x4 inch braces between the ceiling beams. The PVC transparent cover film is fastened with S-clamps onto the main 2x8 inch roof beams. The weight of the center-suspended condensate collector contributes to the vapor seal and shapes the V-cover so that distillate drains to the collector. The result is an inexpensive waterproof roof which provides a supply of fresh water. Accidental cover damage would, at worst, allow rain to drain into the condensate collector. PVF covers have produced the highest yields for solar stills. [103]

In the Soviet Union large solar stills are used both for industrial and agricultural purposes. A reinforced concrete still was built in 1970 in the Shafrikan collective farm at Bukhere Oblast in the Uzbek Republic. [104] The water in that area was unusable for many purposes because of its very high mineral and sulfur content. With an evaporative area of 6500 ft^2, the still produces a yearly average of 0.08 gallons/ft^2 per day, a total of about 540 gallons per day on the average. The still consists of 39 glass covered independent sections of 168 ft^2 each with a trough depth of 10 cm. The maximum output of 80 gallons/hour occurs between 2 PM and 4 PM (in August) and a minimum output of 5 gallons/hour is produced between 3 AM and 7 AM. Another large still uses steps inclined at a 2° to 3° angle so the water flows over the steps,from upper to lower, until it reaches the discharge drain. This flow enhances evaporation and increases the output and efficiency of the still about 20%.[105]

The Krzhizhanovsky Power Institute in Moscow has also been studying various aspects of solar stills. Baum[106] conducted theoretical studies of heat and mass transfer processes in solar stills of the hotbox type and developed techniques for calculating the performance of these stills. He described the basic process occurring in these solar stills as follows. "In an adequately designed still the greater portion of the solar energy that passes through the glass (or film) is spent on evaporation of saline water. As a result, the space within the still is filled with a steam-air mixture. The energy-balance conditions during operation of the still are such that the surface of the glass is at a lower temperature than that of the steam-air mixture, with the result that water vapor condenses on the glass surface, whereas the condensate runs down the inclined glass, drips into the groove and is collected in the tank." He constructed a very well instrumented solar still to investigate these processes. During the tests the temperature of the water heated by the sun varied from 74°F to 207°F while the temperature of the glass condensing surface varied from 61°F to 192°F. As a result of these studies Baum developed equations which accurately describe heat and mass transfer processes in this type of solar still.

Annaev[107] studied the effect of wind speed and direction on the output of a solar still of the greenhouse (glass) type by using a fan to blow air across a small still. For saline water temperatures of 104°F, 131°F and 158°F the wind speed was varied from 0 to 26 feet/sec at wind directions of 0, 45, 90, 135 and 180°; and for all wind directions and temperatures the maximum still output was achieved for a wind velocity of about 16 ft/sec. The reason is that increasing the wind velocity up to this value increases the rate of heat removal from the glass cover, which increases the rate of condensation on the glass resulting in an acceleration of the evaporation process and as much as a 25% increase in still output. Further increases in wind speed lead to a reduction in the saline water temperature which reduces the evaporation rate and still output. The most favorable wind direction is parallel to the condensing surfaces (80° angle). Annaev's data is presented in a table "which can be used for estimating purposes in designing solar stills for a specific site."

CLEAN RENEWABLE FUELS

Most of the energy used in the United States today comes from fossil fuels produced many years ago from solar energy. Clean renewable fuels to supplement and eventually replace these fossil fuels can be produced from plant life grown under more optimum conditions than found in nature, and from organic waste materials. The various processes for the production of these fuels listed in figure 37 are aimed at converting organic materials with a low heating value per unit weight into higher heating value fuels similar to the fossil fuels currently in use. Another possible technique is the use of high temperature heat from solar concentrators to operate a regenerative thermochemical cycle for the production of hydrogen; the hydrogen can be used directly or utilized for the production of hydrocarbon fuels such as methane.

Perhaps the oldest and simplest technique for the production of a clean renewable fuel is to grow plants and burn the plants for energy. Szego [108] has proposed that this be done on a large scale for electric power generation. Air pollution from such a plant is minimal since virtually no oxides of sulfur are produced, particulate emissions can be controlled with precipitators, and the CO_2 released is reabsorbed by the growth of new plants. Up to 3% of the incident solar energy can be absorbed by plants [13, 109], and this energy is released when the plants are burned. For a 1000 MWe steam-electric power plant operated at a load factor of 75% with a thermal efficiency of 35%, 150 square miles of land area is required to fuel the plant if the average insolation is 1400 BTU/ft^2 - day and the capture efficiency of the plants is 3%. Szego [108] calculated the total cost of the fuel to be \$0.06/MBTU for a \$250/acre land cost, 1400 BTU/ft^2 - day insolation, 3% capture efficiency, 8% interest rate, 0.6% tax rate, and \$200/acre harvesting cost, and the total cost of the electric power

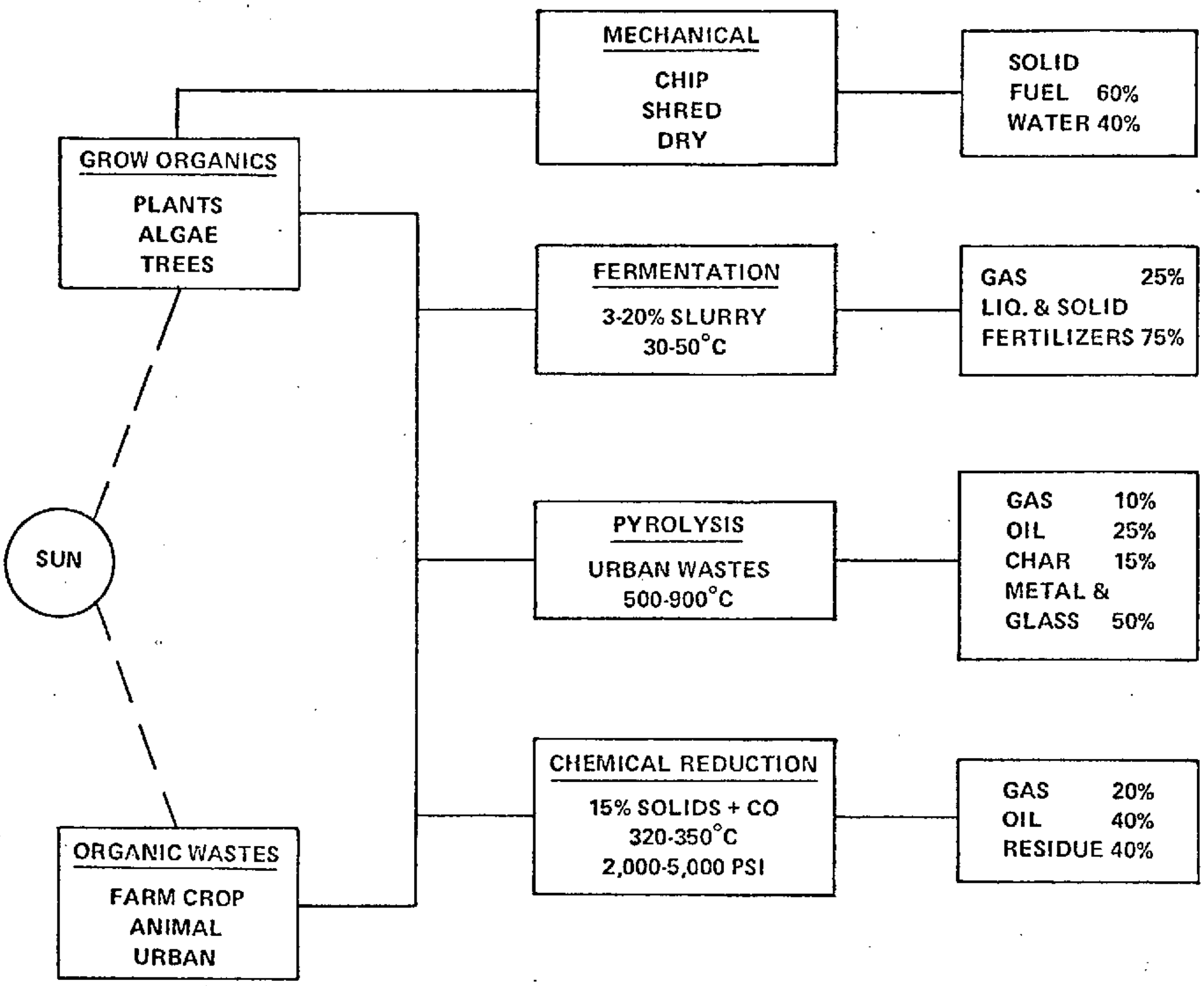


Figure 37. Processes for Producing Fuels from Solar Energy [13]

from this "energy plantation" is computed to be 5 mills/KWh, based on a $200/KW capital cost and 28 year life for the power plant. A "worst case" fuel cost is $0.40/MBTU if the capture efficiency is reduced to 1% and the harvesting cost increased to $700/acre, which results in a power cost of 8.5 mills/KWh. The annual operating cost is taken to be $2 million/year, and insurance and tax costs 0.12% and 2.35% of the capital cost of the power plant. Szego concluded that this type of plant would "cost no more to build and maintain than a conventional fossil fuel steam electric plant" and that "the energy plantation is a renewable resource and is an economical means of harnessing solar energy." It is not at all obvious at the present time what type of plant (trees, grasses, etc.) will result in the lowest power costs. The NSF/NASA Solar Energy Panel [13] concluded that using trees the fuel cost at the power plant might range from $1.50 to $2.00/MBTU.

Some power can also be produced by the combustion of organic wastes, which also reduces problems of disposal of these wastes. It has been estimated [13] that the total animal and solid urban wastes which can be collected at reasonable cost could provide about 6% of the heat energy requirements for electric generating plants. The most promising use of solid animal wastes is in connection with large feedlot operations where large quantities are accumulated at one location and disposal presents a continuing problem.

Anaerobic fermentation of organic materials results in the production of methane and carbon dioxide. This process can be used (Figure 38) to convert from 60% to 80% of the heating value of organic materials into methane, which can serve a wide variety of uses including powering automobiles. Methane can also be used in existing natural gas pipelines. Algae grown in sewage ponds can also be used for the production of methane; costs of producing methane by this method are estimated between $1.50 and $2.00/MBTU.[13]

Pyrolysis has also been used for many years to convert organic materials to gaseous, liquid and solid fuels. Any organic materials can be used, and in addition plastics, rubber products, and other similar materials can also be used. The gases produced are a mixture of hydrogen, methane, carbon monoxide, carbon dioxide, and hydrocarbons. About two barrels of oil can be produced per ton of dry organic material. A plant handling 1000 tons of waste per day (Figure 39) could dispose of the solid wastes produced by a city of 600,000 people.

At temperatures around 600°F and pressures between 2000 psi and 4000 psi organic materials can be partially, converted into oil. In laboratory tests oil yields up to 40% of the weight containing about 2/3 of the heating value

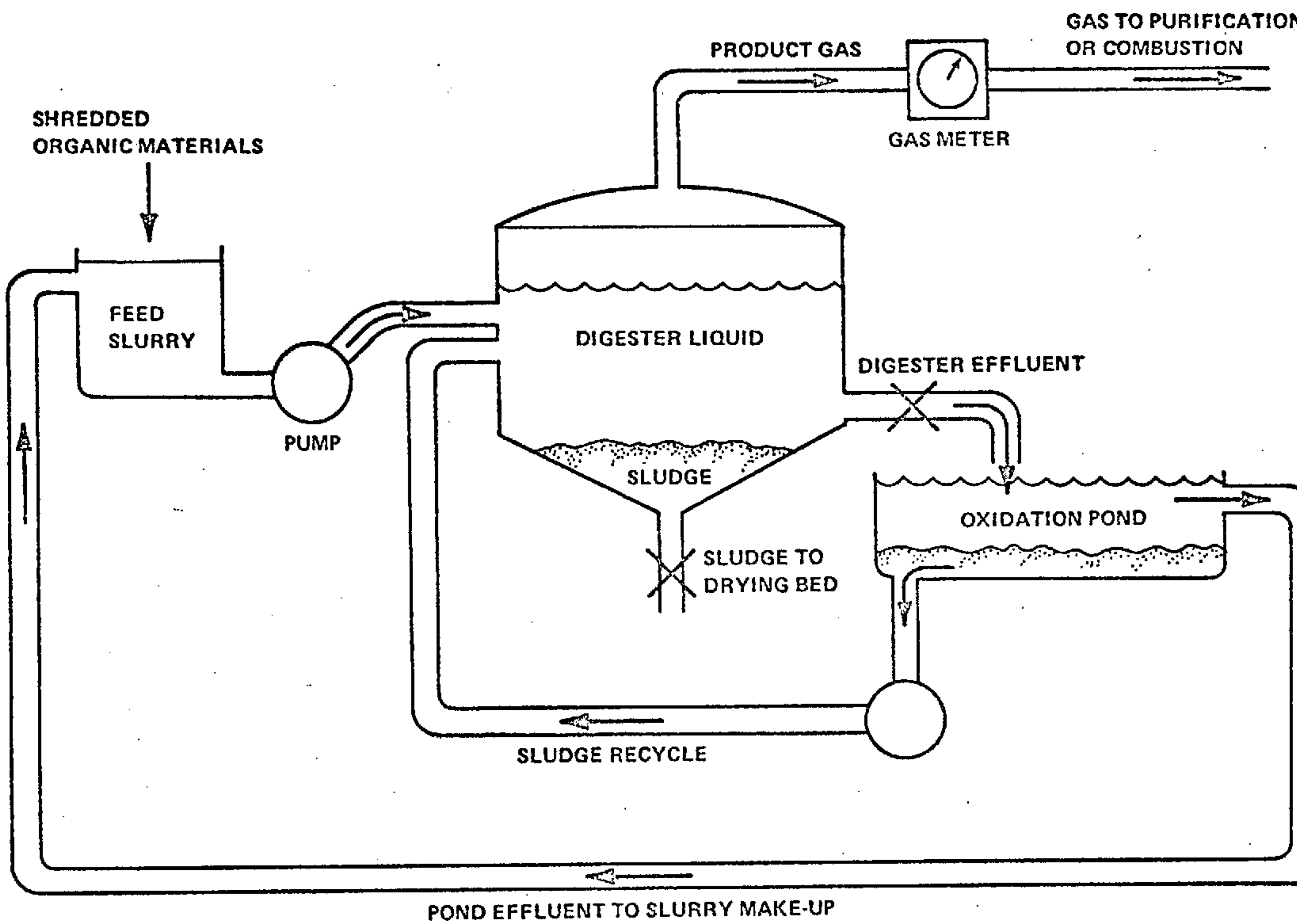


Figure 38. Anaerobic Fermentation System For the Production of Methane[13].

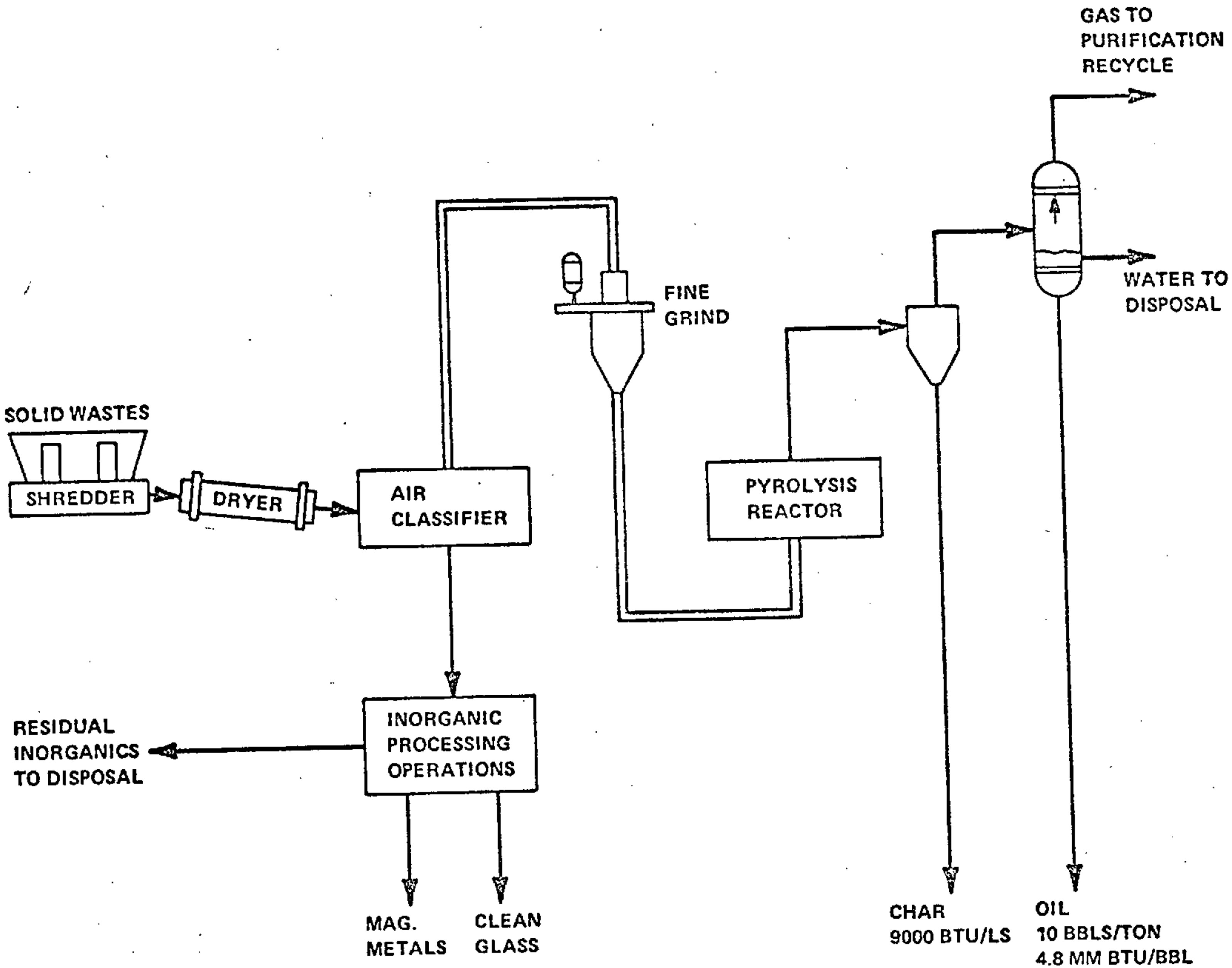


Figure 39. Schematic of Solid Waste Pyrolysis Plant[13].

of the initial dry organic matter have been obtained.

Hydrogen may be thermochemically produced directly from water using solar heat. For example a regenerative chemical cycle proposed by DeBeni [110] operates with bromides of calcium and mercury in a four step process with a maximum temperature of 1350°F. The four reactions are

1)	$CaBr_2 + 2H_2O$	$\rightarrow$	$Ca(OH)_2 + 2HBr$	1350°F
2)	$Hg + 2HBr$	$\rightarrow$	$Hg\,Br_2 + H_2$	480°F
3)	$HgBr_2 + Ca(OH)_2$	$\rightarrow$	$CaBr_2 + HgO + H_2O$	400°F
4)	HgO	$\rightarrow$	$Hg + (0.5)O_2$	900°F

The net result of these four reactions is:

$$H_2O \rightarrow H_2 + (0.5)O_2$$

Water is thus seperated into hydrogen and oxygen at temperatures easily obtainable by linear concentrators in large solar farms. The hydrogen and oxygen are released at separate points in the cycle, and the chemicals used are regenerated permitting virtual 100% recovery of the chemicals without sideloops. One drawback is the large amount of materials circulation per unit product. This cycle is an example of a number of regenerative thermo-chemical cycles that have been proposed for the production of hydrogen with temperatures obtainable on a large scale with solar concentrators.[111]

Figure 40 illustrates the relative 1972 cost of solar-produced clean renewable fuels and fossil fuels. The costs of fossil fuels are now rising rapidly, so solar synthetic fuels are going to continue to become increasingly competitive.

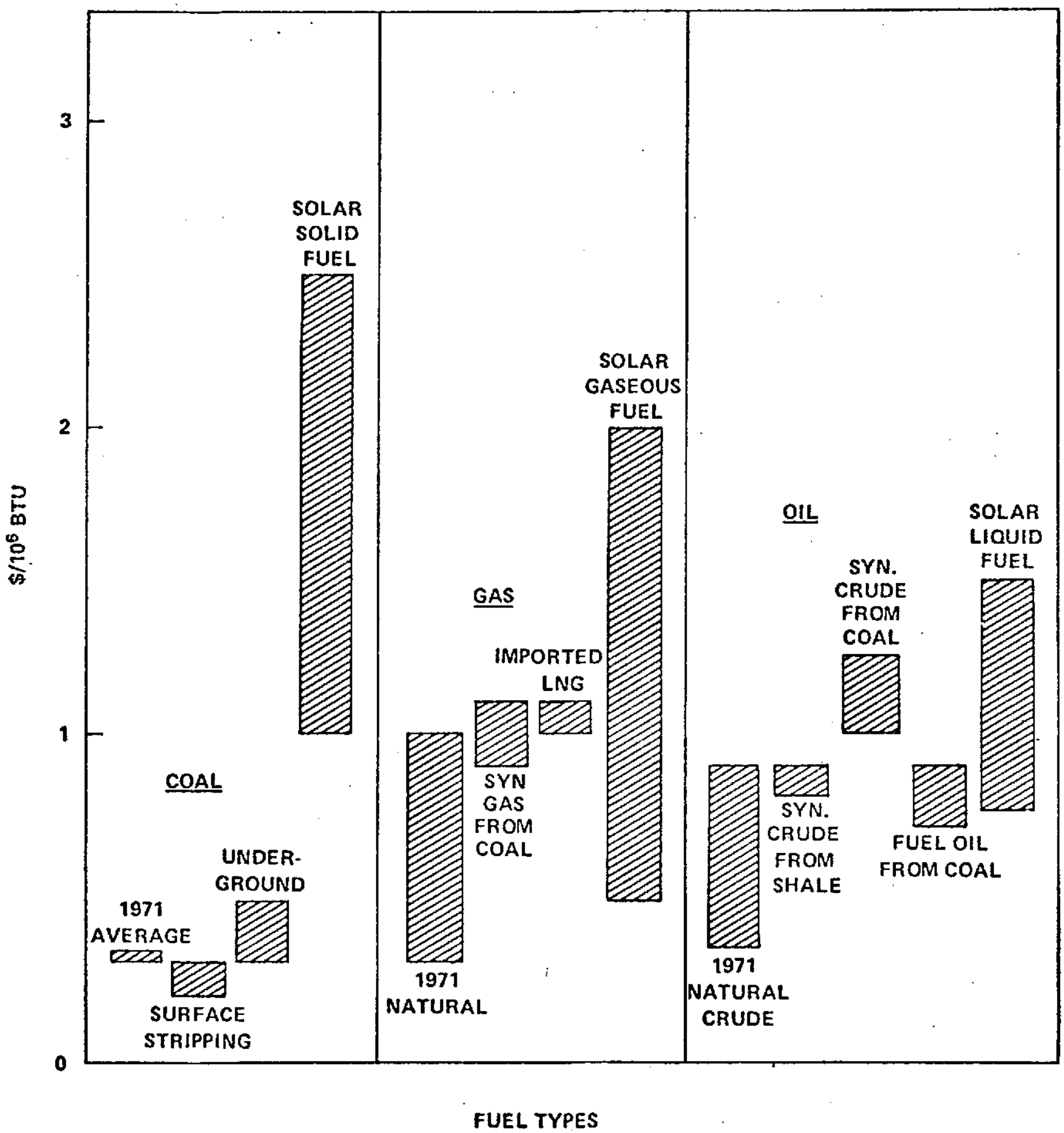


Figure 40. 1972 Costs of Fossil and Solar Renewable Fuels.

OCEAN THERMAL POWER

The French physicist Jacques D'Arsonval [112] suggested in 1881 that a heat engine operating between the warm upper layer and the cold deep water of the tropical oceans could produce large amounts of power. Although the engine must be inherently inefficient, the amount of heat available is enormous, and since this heat comes from the sun, ocean thermal power is appropriately classified as a form of solar power. D'Arsonval suggested a number of possible high vapor pressure working fluids, including ammonia.

In 1929 Claude [113], a friend of D'Arsonval, demonstrated a 22 kilowatt ocean thermal power plant in Mantanzas Bay, Cuba (Figure 41), but due to its low efficiency (< 1%) the plant was not economically competitive with other power plants at that time. Claude used surface sea water admitted to a low pressure evaporator to provide low pressure steam to drive the turbine. This low pressure steam was then recondensed by direct contact with cold seawater in a spray condenser. The Claude cycle avoided large heat exchangers required by closed cycle plants to vaporize and recondense a high vapor pressure working fluid, but did require a large turbine of inherently low efficiency. The relatively high vacuum required maintaining large leak-tight connections and the removal of dissolved gases from the water. The plant itself was located on land and 2Km long tubes brought cold water from the depths, with resulting heating of the water as it flowed through the tubes. In spite of the economic failure of the project, Claude's plant was the first to demonstrate power generation from ocean temperature gradients.

Two large experimental power plants of 3.5 MWe each using the Claude cycle were built by the French at Abidjan off the Ivory Coast in 1956 to utilize a thermal differance of 36°F. An 8 foot diameter pipeline was built extending to a depth of 3 miles about 3 miles from shore, but difficulties in maintaining this pipeline prevented the plant from operating at full capacity. About 25%

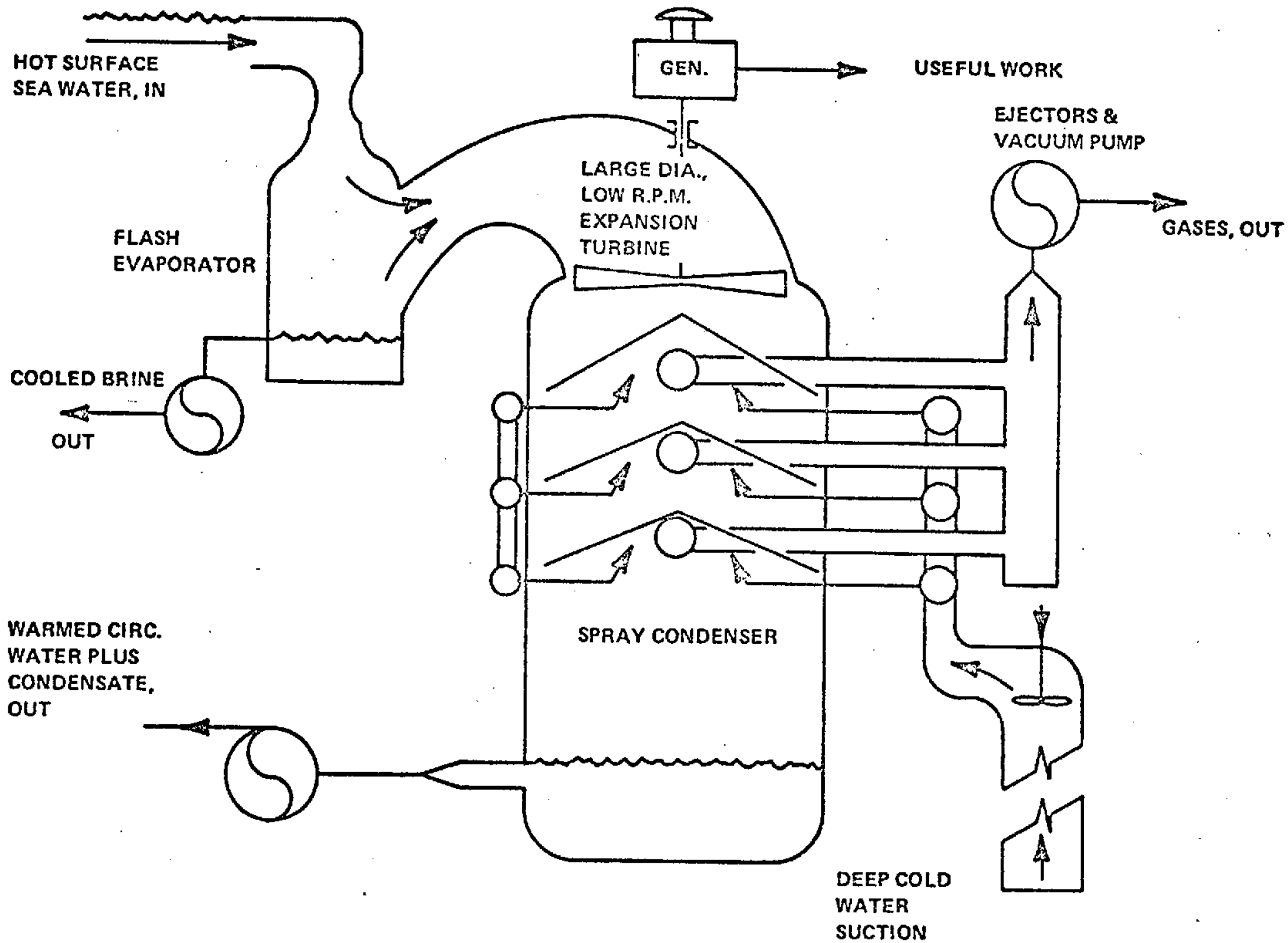


Figure 41. Claude's Ocean Thermal Power Plant

of the power generated was required for the pumps and other plant accessories. The plants were finally abandoned.

Two approaches to improving the Claude cycle are the use of controlled flash evaporation as proposed by Roe [114], and the indirect vapor cycle proposed originally by D'Arsonval. Roe's system (Figure 42) illiminates major problems of deaeration and seawater corrosion associated with the Claude cycle and produces fresh water in addition to electric power. The flash evaporator consists of a large number of parallel vertical chutes with films of warm seawater flowing down (Figure 42). As the pressure drops, water evaporates and the vapor flows downward. This low pressure steam then flows

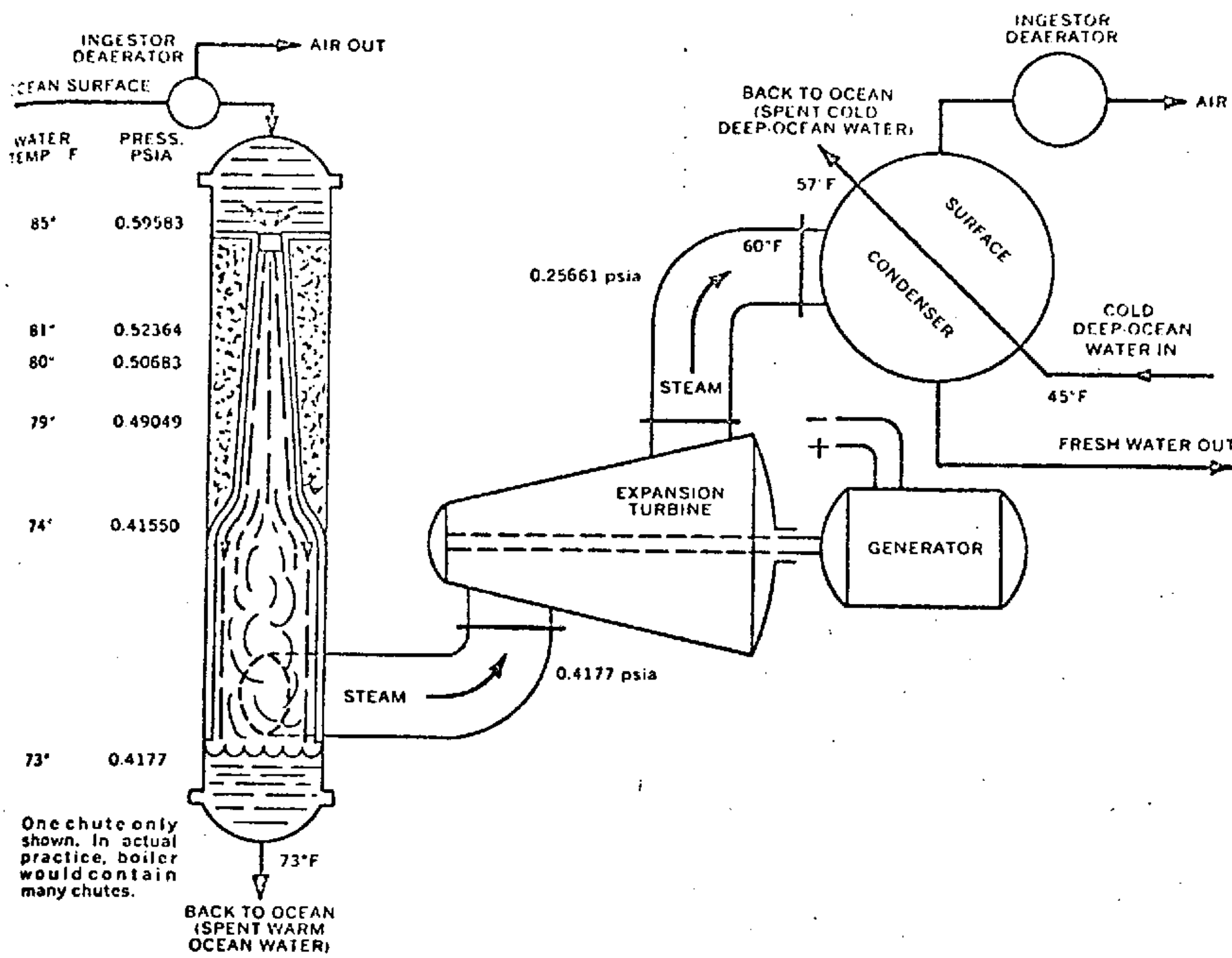


Figure 42. Controlled Flash Evaporation Ocean Thermal Power Plant [115]

through the large low pressure turbine and into the condenser where it is cooled and condensed by cold seawater from the ocean depths. If fresh water is not desired, steam from the turbine can be condensed by direct contact with cold seawater (as in the Claude cycle) with a slight increase in power output. Deaeration in this cycle is accomplished at a low cost with practically no power requirement. About 11.5 gallons of pure water can be produced per 1000 gallons of warm water circulated.[115] This system still suffers from the large, inherently inefficient low pressure steam turbine.

The indirect vapor cycle requires the addition of a boiler, but permits the use of higher pressure working fluids with a much smaller and more efficient turbine. Since the efficiency of ocean thermal plants will be only about a tenth that of modern steam plants, the amount of heat transferred in the boiler and condenser per unit power output must be about ten times as large. It does not follow, however, that the costs of these components will be ten times as great. Since ocean thermal plants will operate at relatively low pressures and ambient temperatures, the tube wall can be thinner and cheaper materials can be used, so the cost per unit of heat transfer should be much less for ocean thermal boilers and condensers than for those used in high temperature steam plants.

Anderson[116] proposed a floating power plant using propane as the working fluid (Figure 43). Seawater from the warm surface layer is passed through the boiler to vaporize propane at about 150 psi. The propane exhausted from the turbine is condensed at about 110 psi by cold seawater. In 1965 the Andersons estimated the capital cost of this plant at $168/KW, which was comparable to the capital cost of a fossil-fueled plant at that time. In order to equalize pressure differances in the boiler and condenser, the Andersons proposed that the plate heat exchanger acting as the boiler be lowered to a depth of 290 feet and the plate condensers lowered to 150 feet, with the turbines and other components at intermediate depths. Zener[117] has suggested a modular design

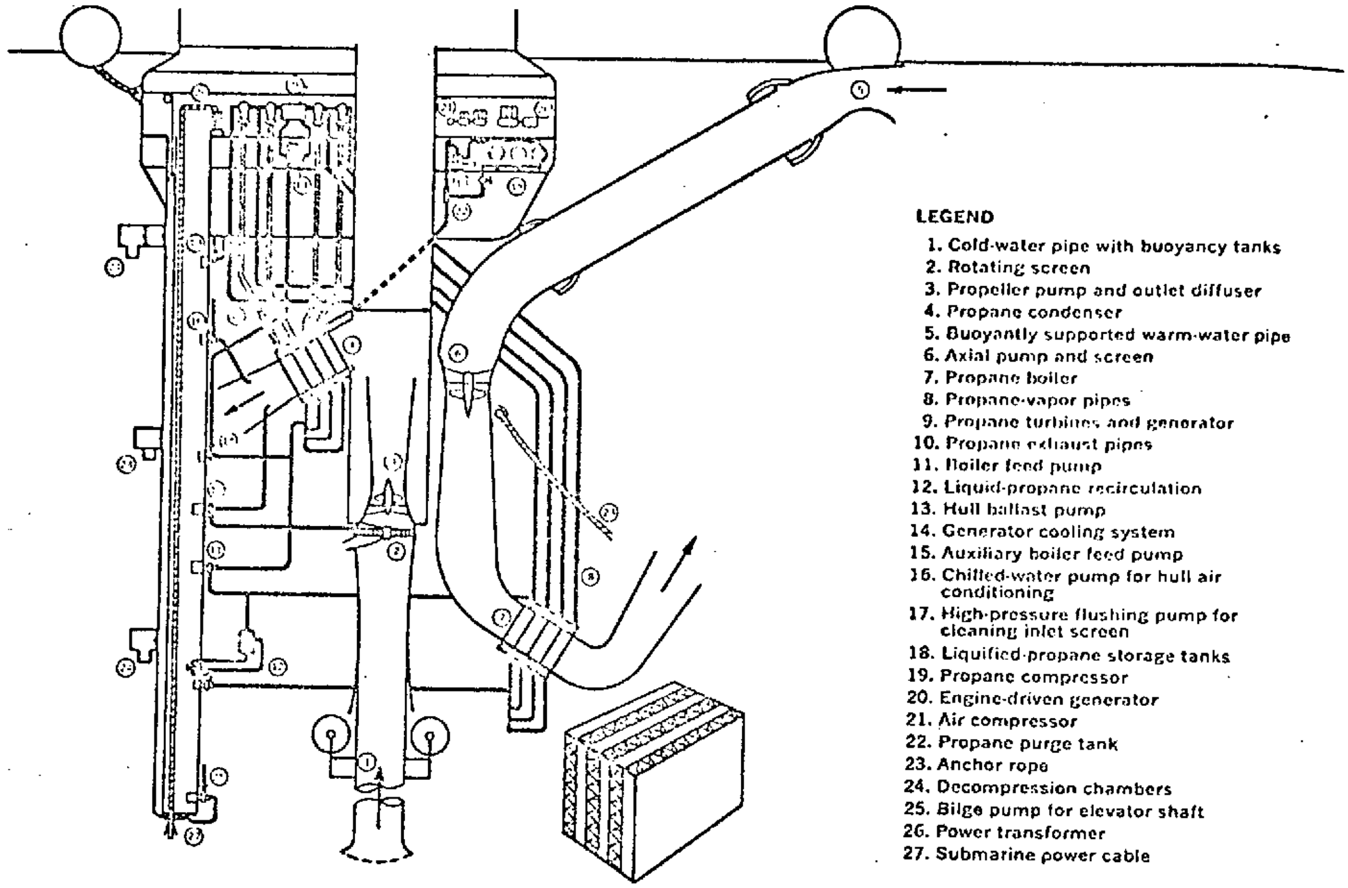


Figure 43. Floating Propane Ocean Thermal Power Plant [115]

with the boiler, condenser and engine modules all of the same standard size, such as 8 ft by 8 ft by 40 feet (Figure 44). The modular system should reduce manufacturing, transportation, and assembly costs. The plant would be neutrally buoyant at the depth which minimizes the pressure differances in the boiler and condenser.

McGowan [118] et. al. with NSF/RANN support have conducted an analysis of ocean thermal power plant concepts from 100 to 400 MWe using various working fluids. Figure 45 is a schematic of their system and a generalized temperature entropy diagram; characteristics of potential working fluids are given in Table 8. The ideal cycle efficiency in Table 8 is based on a maximum cycle temperature of 65°F and a minimum cycle temperature of 45°F. Ammonia is the best working fluid from the heat transfer standpoint. McGowan [118] presents a comparison of the other working fluids with ammonia as follows:

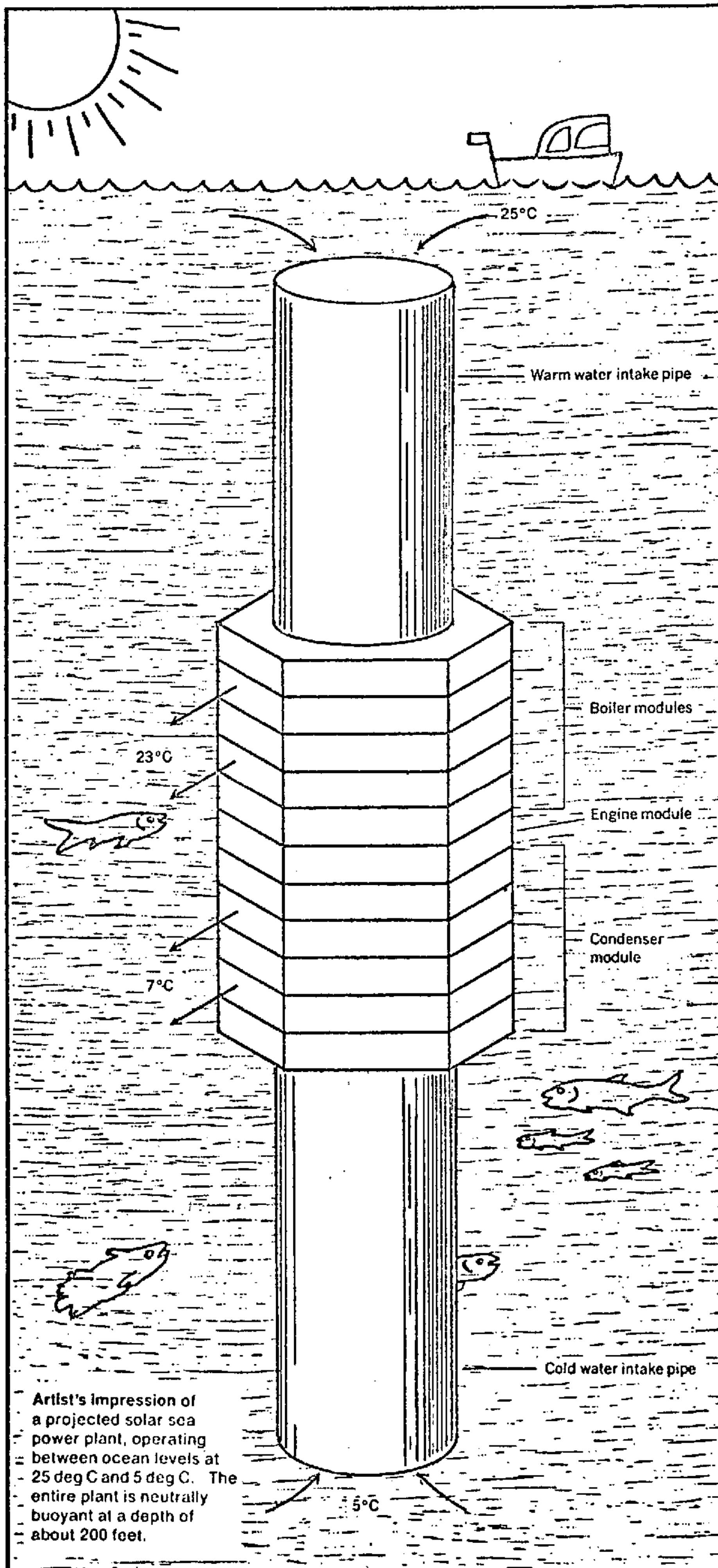


Figure 44. Modular Ocean-Thermal Power Plant[117]

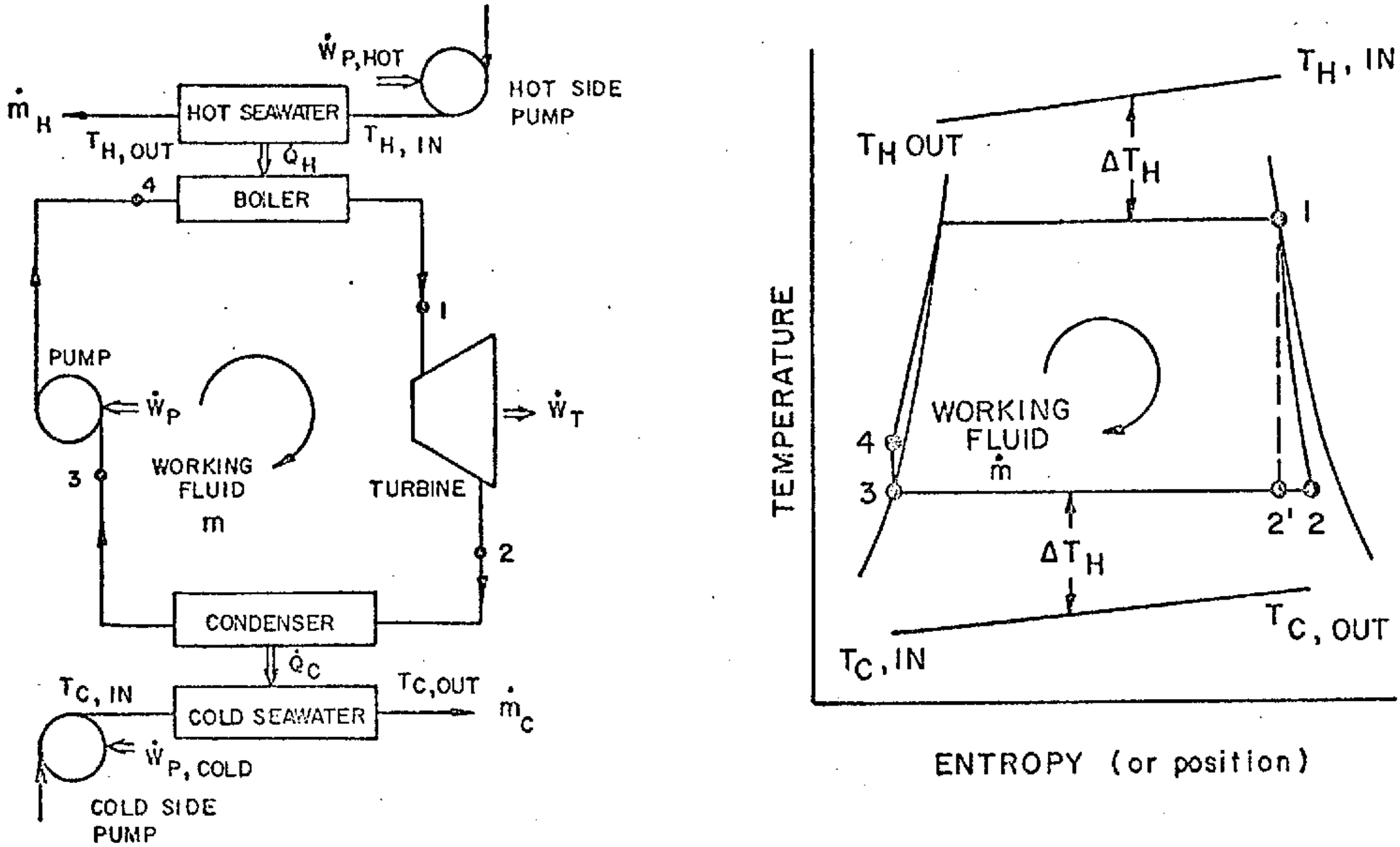


Figure 45. Schematic and T-S Diagram for Ocean Thermal Power Plant [118]

Table 8. Comparison of Working Fluids[118]

FLUID	IDEAL CYCLE EFFICIENCY (%)	CYCLE EFFICIENCY (5% ΔP/P)	HIGH PRESSURE (psia)	LOW PRESSURE (psia)	PUMP WORK (kw)	IDEAL MASS FLOW (lb/min)
Ammonia	3.72	2.71	118	81	1079	317,600
Butane	3.82	2.81	29	20	859	976,000
Carbon Dioxide	2.89	1.67	799	609	36,033	2,873,000
Ethane	3.90	2.04	53	411	25,300	1,495,000
R-12	3.68	2.57	78	56	2,450	2,630,000
R-22	3.68	2.54	126	91	3,200	1,978,000
R-113	3.65	2.91	5	3	170	2,436,000
R-500	3.67	2.55	92	66	2,750	2,205,000
R-502	3.61	2.41	140	103	4,552	2,756,000
Propane	3.67	2.46	115	85	3,706	1,084,000
Sulphur Dioxide	3.72	2.82	45	30	634	1,041,000
Water	3.78	3.26	0.3	0.15	1.4	155,500

Table 9. Heat Transfer Coefficients of Working Fluids

FLUID	RELATIVE h condensing	RELATIVE h boiling
Ammonia	1	1
Butane	0.15	0.32
Carbon Dioxide	0.18	0.18
Ethane	0.11	0.21
R-12	0.11	0.11
R-22	0.16	0.14
R-113	0.09	0.13
R-500	0.12	0.13
R-502	0.10	0.11
Propane	0.13	0.27
Sulphur Dioxide	0.38	0.33
Water	0.92	2.27

They also considered a variety of heat exchanger geometries illustrated by Figure 46. For ammonia a single stage turbine with a 7 foot wheel diameter would generate 25 MW at 1800 RPM, for propane a 12 foot wheel diameter single stage turbine could produce 30 MW at 600 RPM. Propane and ammonia appear at present to be the most attractive working fluids.

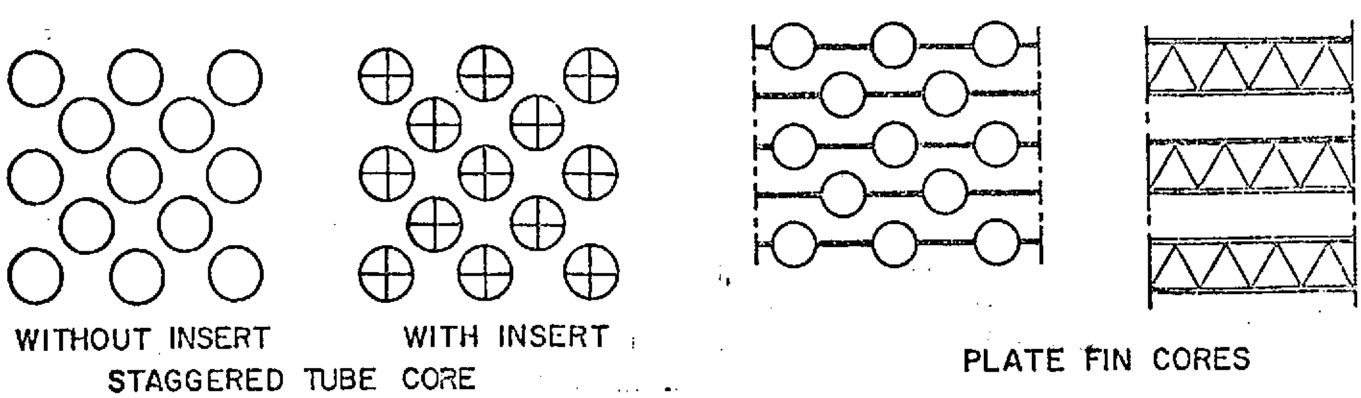


Figure 46. Potential Heat Exchanger Geometries

The amount of energy available for ocean thermal power generation is enormous, and is replenished each year as the sun heats the surface layers of oceans and melts snow in the arctic regions causing cold currents to flow deep beneath the surface toward the equater. According to Zener, "the tropical oceans in the year 2000 could supply the whole world with energy at a per capita rate of consumption equal to the US per capita rate in 1970 and suffer only a one-degree C drop in temperature." Also, if nutrient-rich cold water is brought from the ocean depths and released near the surface, this could result in a substantial increase in fish populations, as occurs naturally off the coast of Peru. Another advantage could be a slight lowering of tropical temperatures. Figure 47 gives the surface and underwater temperatures in the straits of Florida just 30 miles from Miami. At a depth of 1300 feet the temperature is 43°F, as compared with a surface temperature from 75°F to 84°F.

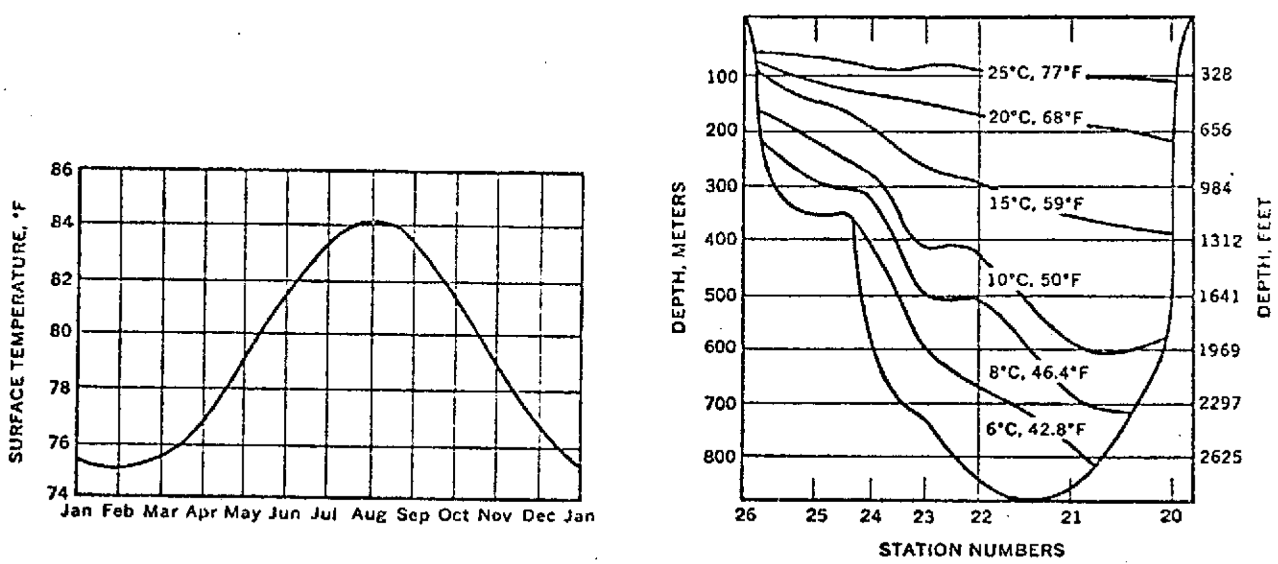


Figure 47. Water Temperatures in the Straits of Florida.[115]

Anderson[119] has recently proposed an "sea plant" with a floating propane cycle ocean-thermal electric power plant, a separate ocean-thermal flash - evaporation plant for producing pure water, and various chemical industries based on extracting oxygen and new materials from the ocean. Noting that the Gulf Stream alone could supply 200 times the total power requirements of the United States, he estimates the cost of a 100 MWe plant at $20 million

($200/KWe) and cost of fresh water at $0.04 per thousand gallons. This cheap power and cheap water makes possible a variety of energy intensive chemical process plants. Oxygen gas, extracted from seawater, could be liquified using propane turbines to drive the refrigeration compressors, and cold water from the ocean can be used as a convenient heat sink at lower than usual ambient temperatures. Chemical plants using raw materials extracted from seawater would benefit from the cheap power. Bromine and magnesium are already being produced commercially from seawater [120]. In addition, one of the best ways to transmit power to shore may be to electrolyze water to produce hydrogen and oxygen, and then liquify these gases, which can then be shipped or piped to shore. Anderson concluded that "sea thermal power is potentially a profitable enterprise. At this stage of development it appears to have far better economic potential than any other scheme to utilize solar energy for power production."

GEOSYNCHRONOUS POWER PLANTS

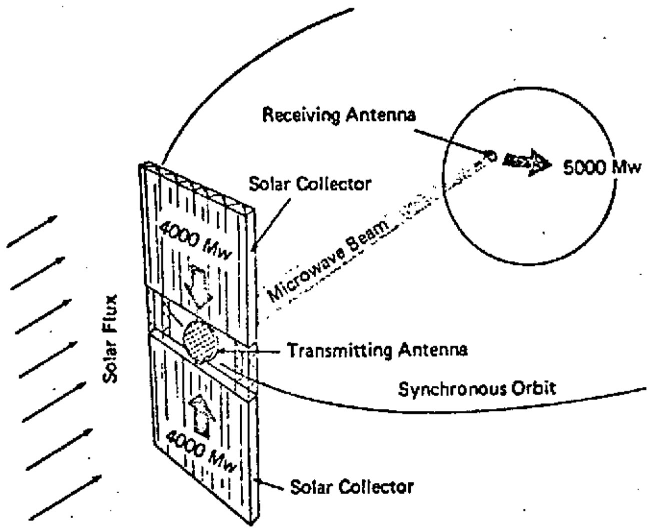
The concept of placing a large solar array in geosynchronous orbit and transmitting this power to earth was proposed by Glaser[121, 122] in 1968, and since has received increasing attention as a potential major energy resource for the next century. The basic motivation for placing the solar array in space is the increased availablity of solar energy in space, as illustrated by Table 10. Fifteen times as much solar energy is received

Table 10 - Average Availabilities of Solar Energy[123]

AVAILABILITY FACTOR	AVERAGE ON EARTH	IN SYNCHRONOUS ORBIT	AVERAGE RATIO
Solar Radiation Energy Density	0.11 watts/cm^2	0.14 watts/cm^2	4/5
Percentage of Clear Skies	50%	100%	1/2
Cosine of Angle of Incidence	0.5	1.0	1/2
Useful Duration of Solar Irradiation	8 hr.	24 hr.	1/3
PRODUCT			1/15

by a solar array in space as the same array would receive on the ground, and this energy is received continuously, 24 hours a day. Now that NASA is developing the space shuttle to permit the routine exploitation of the space enviroment, the economics of geosynchronous power plants are becoming more attractive.

The basic concept, as proposed by Glaser, is illustrated by Figure 48. concentrators would reflect sunlight onto an advanced, lightweight solar array. The two symmetrically arranged collectors convert solar energy directly to electricity which powers microwave generators with the transmitting antenna located between the two large collecting panels. The 1 Km diameter antenna transmits the power to a 7.4 Km diameter receiving antenna on the ground (Figure 49) with an overall efficiency of about 68%. The microwave transmission system is expected to cost \$130/KWe.[125] In order to achieve the



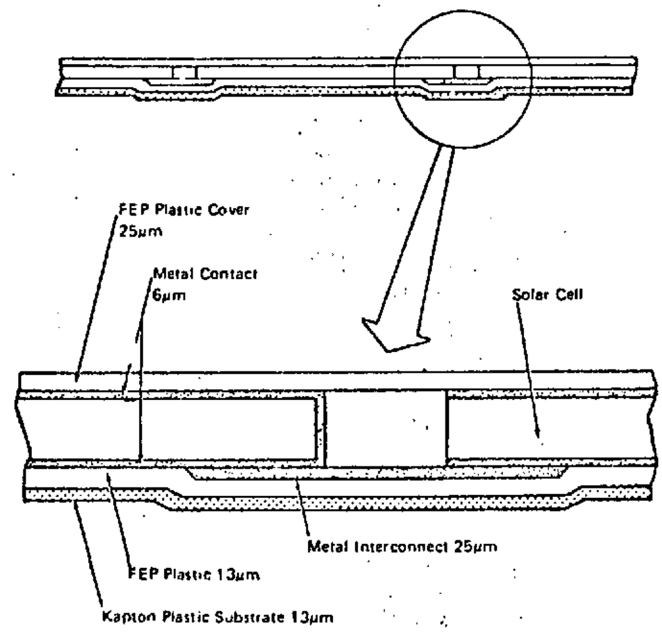


Figure 48. A) Geosynchronous Solar Power Plant [124]
B) Solar Cell Array Construction [125]

necessary coherent transmission, the many separate elements of the transmitting antenna must be phase locked onto a pilot signal originating from the center of the receiving grid, and it is impossible to direct the beam away from the receiving antenna. Since the receiving grid does not block sunshine, the land beneath can be used for growing farm crops. Microwave intensities reaching the earth are completely safe.

The solar cells in the array are projected to have an 18% efficiency, 2 mil thickness, and cost \$0.28 per cm^2, which should lead to a 430 W/lb array costing \$0.68 per cm^2 and having a 30 year life. The array is expected to suffer a 1% loss of solar cells from micrometoroid impacts over a 30 year period. Glaser [125] gives the cost of a small several hundred megawatt prototype plant, based on current shuttle cost estimates and near-term solar cell

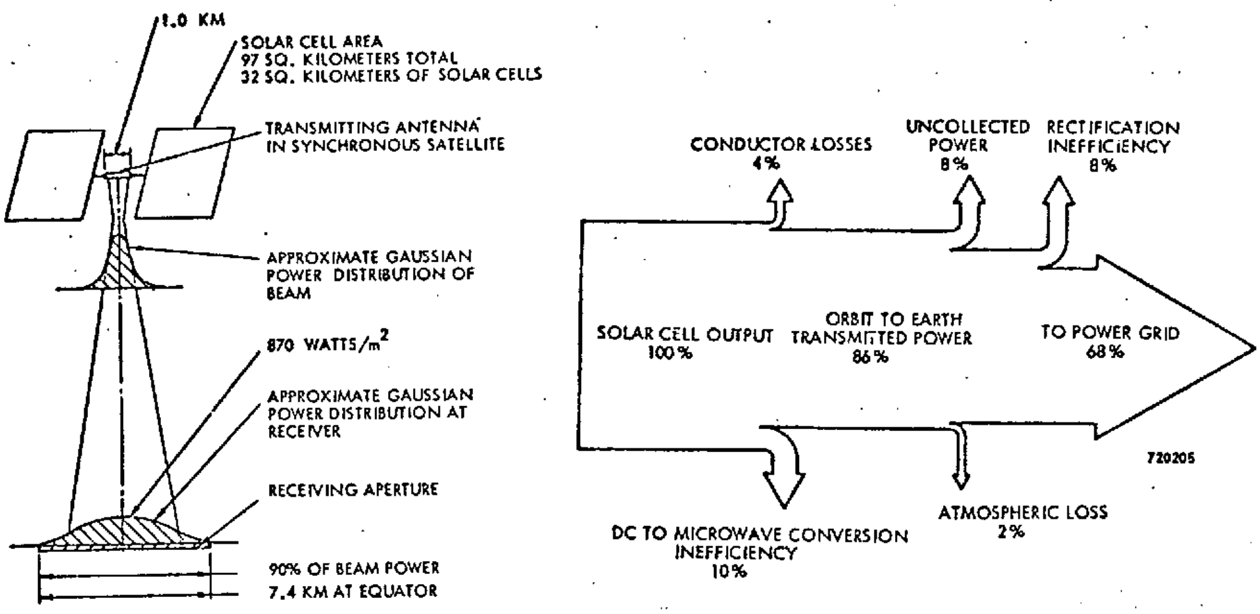


Figure 49. Microwave Transmission to Earth [126]

technology, as \$310/KWe for the solar arrays, \$230/KWe for the microwave transmission system, and from \$800/KWe to \$1380/KWe for transportation to geosynchronous orbit and assembly, for a total system cost of from \$1340/KWe to \$1920/KWe. Capital cost for a fully operational 5000 MWe plant is expected to be about \$800/KWe. The power satellite will produce more energy in its first year of operation than was required to manufacture it and place it in orbit.

Patha and Woodcock [127] explored the feasibility of large geosynchronous solar-thermal plants (Figure 50) operating with a "current technology" helium/xenon brayton cycle, and estimated the capital cost of a 1980 technology plant at \$2540/KWe. Since about 80% of this cost is space transportation, this cost should be reduced if a fully reusable space shuttle becomes operational and lighter weight reflecting surfaces become available. They also projected an advanced solar cell system to cost \$2950/KWe, slightly more than the solar-thermal system. Brown [128] projected the capital cost of solar cell geosynchronous plants to lie in the range of \$1400/KWe to \$2600/KWe. Mockovciak [129] reported

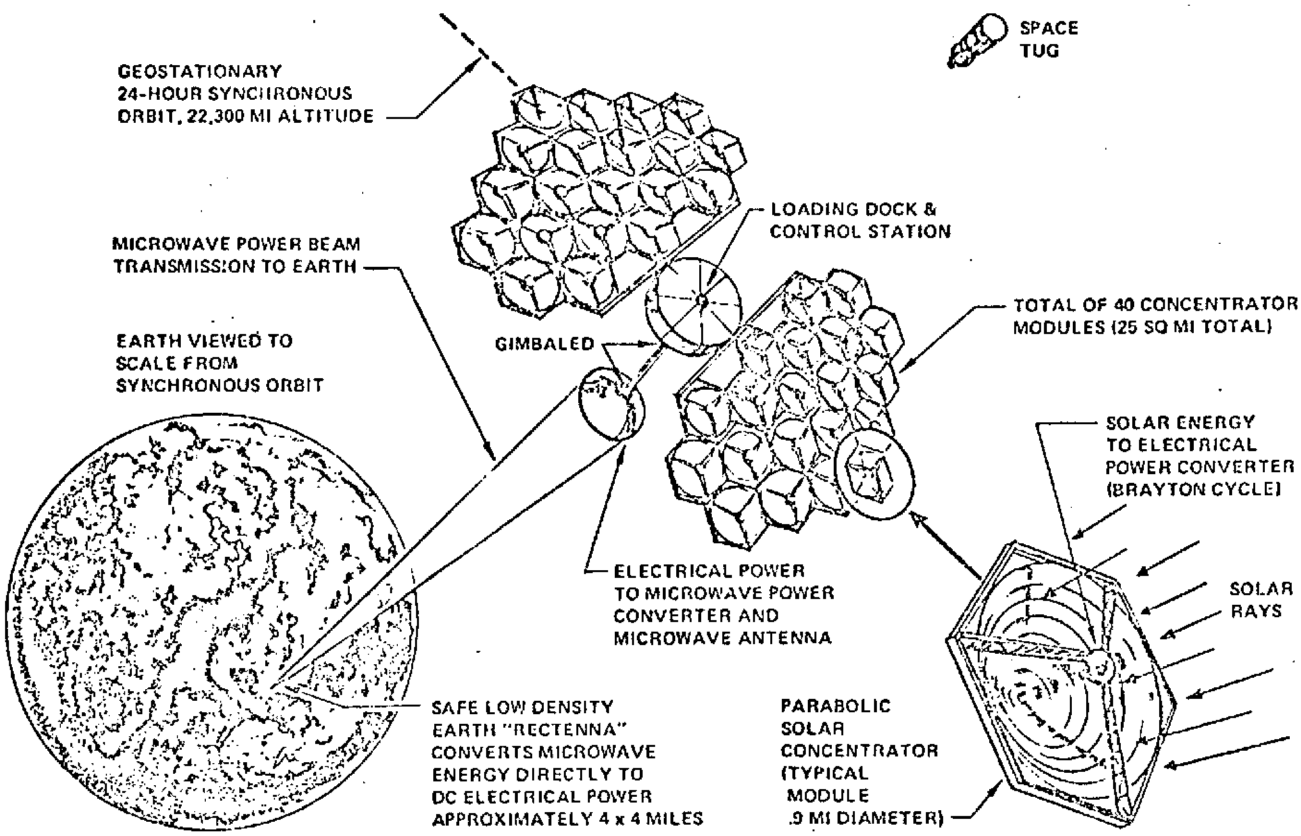


Figure 50. Geosynchronous Solar-Thermal Power Plant

an earlier estimate of $2100/KWe for a protype solar cell plant based on a study by the A.D. Little/Grumman/Raytheon/Textron team. This group has been conducting a study of the solar cell system for several years.

RECOMMENDATIONS AND PROJECTIONS

Figure 51 illustrates the energy flow pattern that occurred in 1970, and the energy flow pattern for 1985 projected by the Joint Committee on Atomic Energy [130]. Oil imports were projected to increase from 3.5 million barrels/day to 14.6 million barrels/day by 1985, and natural gas imports were projected to increase by a factor of 6. Since these projections were made, foreign oil prices have increased as much as a factor of 5, and the Arab embargo has cut foreign oil imports almost in half. Even if the embargo ends, the high price of foreign oil (over $11/barrel) will make the projected imports economically unfeasible. At current prices the projected imports would cost over $60 billion in 1985 alone.

In view of the economic and political realities now facing this country, the President has declared a national goal of "energy sufficiency by 1980." If the United States is to become self sufficient in its energy resourcesby 1980, or even a few years thereafter, new domestic energy sources must be rapidly developed. Solar energy represents a virtually untapped domestic energy resource which can be very rapidly utilized to reduce fossil fuel requirements.

Solar energy should be developed and used as rapidly as possible, so the following recommendations are made for research, development and demonstration programs in solar heating and cooling, solar electric power generation, and the development of clean, renewable fuels. Wind, ocean currents, and flowing rivers are not included in this study. The following recommendations are listed under the major headings of RESEARCH - highest priority research programs, DEVELOPMENT - development of manufacturing techniques for economically mass producing devices already existing in the laboratory, DEMONSTRATION (3 years) - large scale system demonstrations

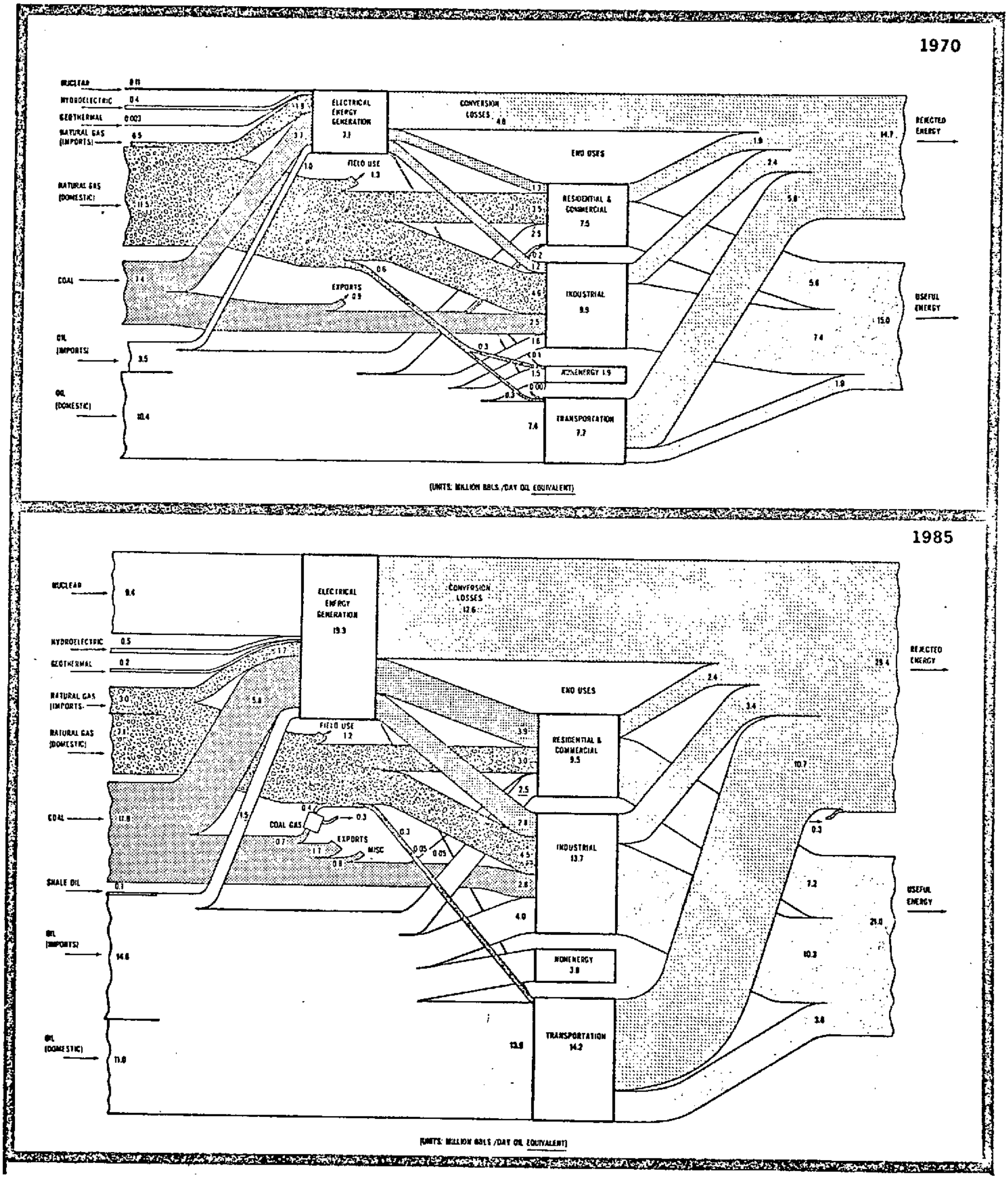


Figure 51. Energy Flow Patterns 1970/1985 130

within 3 years, DEMONSTRATION (8 years) - system studies now, then design, then demonstration within eight years, and DEMONSTRATION (15 years) - systems requiring as much as 15 years to demonstrate if work begins now. All recommendations require immediate action if the systems and devices are to be available in the time frame indicated. They are listed under each heading in order of priority.

Recommendations

RESEARCH

1. Inexpensive, strong, long-lasting, transparent and reflective plastic films should be developed as rapidly as possible. This technology would greatly improve the economics of a variety of solar energy systems.
2. Long-life, cheap, rugged, reasonably efficient solar cells which can be easily assembled into arrays and which will operate at moderately high temperatures (250^{o}F). Major efforts should be devoted to developing new types of solar cells and improving their performance.
3. Plants with high capture efficiency for converting sunlight into biomass require intensive study to improve the performance of bioconversion systems.
4. Low cost compact heat storage systems should be developed to improve the performance of solar heating, cooling and thermal power systems, especially phase-change systems.
5. Heat transport devices for collecting and distributing heat cheaply with minimal loss, including heat pipes.

DEVELOPMENT

1. Mass produced cheap solar cells. The highest priority development effort should be the rapid implementation of large scale manufacturing techniques to produce cheap solar cells, using silicon ribbon or sheets [71-74].
2. Mass produced, cheap optical coatings for glass, plastic films, or other materials should be manufactured as soon as possible. These include coatings to increase transmission and coatings to retard infrared emission.
3. Inexpensive, mass produced, durable flat plate collectors, to be made generally available as soon as possible for heating, air conditioning, and water heating. A 4x8 foot collector (without insulation) should cost from $20 to $40, and be easily installed with plastic pipe.
4. Economical absorption air conditioning systems made to operate on hot water from a solar collector should be put on the market. The system should be able to use an auxiliary energy source.
5. Cheap, mass produced tracking devices such as thermal heliotrops, heliostats, and transistorized sun-sensing mechanisms, are needed for solar concentrator systems.

DEMONSTRATION (3 years)

1. Large-scale solar heating and cooling and hot water for homes, apartments, and other buildings using water cooled flat plate collectors, absorption air conditioning, and hot water storage. With federal support these systems could be installed for demonstration purposes throughout the nation in new apartment complexes, subdivisions, etc.. Collectors can also be installed on vertical walls of tall buildings. Collectors should be blended into the building structure in an attractive manner. The purpose of these demonstrations is to prove the economics and acceptability of these systems at various locations throughout the nation.

2. Substation - sized thermal electric power plants which also supply heat, as required, in the form of steam, hot water, or hot air could be built using the more promising concepts for solar-thermal power generation. Hopefully one or more of these plants will be shown to be economically competitive with alternative power sources.
3. High temperature heat supply systems using solar concentrators and a suitable storage system to provide heat for industrial processes are needed. An example would be a six million BTU/hour 400^{o}F hot air supply system for textile drying operations.
4. Clean, renewable fuels (oil and gas) could be produced from organic materials on a small scale to provide badly needed data relating to the feasibility of future large scale production of these fuels.
5. Low-cost single-story housing with roof panels for heating and cooling can be built in sunny areas to demonstrate the economic feasibility of low income housing of this type in sunny areas.

DEMONSTRATION (8 years)

1. Solar cell flat plate collector electric power, heating and cooling systems for homes, businesses, and even tall buildings. All major system components should be mass manufactured with high reliability long life, minimal maintanence and low cost. Compact low cost heat storage should be included. For tall buildings the collectors can be mounted on vertical walls. Solar total energy systems using integrated collectors should be demonstrated with a variety of building types at various locations around the country. Au iliary fuel requirements should be minimized.
2. One or more prototype ocean thermal power plants producing at least 100 MWe plus fresh water should be built, using different cycles, to establish the feasibility of ocean thermal plants and determine which system performs best.

3. A solar thermal electric power plant of 100 MWe or more should be built in a sunny climate. If two or more proposed plant systems are judged equally promising, each should be built. These prototype plants should determine whether or not large scale solar thermal conversion is practical.

4. Prototype clean renewable fuel plants of several types should be built. At least one of these organic conversion plants should process municipal wastes, one receive wastes from a large feedlot, and one or more process plant matter grown specifically for the bioconversionfacility. Cheap, automated techniques for harvesting the plants and transporting the materials to the bioconversion facility, should be developed and used. The primary purpose of these projects should be to demonstrate the economic feasibility of large-scale operations.

5. An energy plantation power plant of at least several hundred MWe utilizing minimum cost harvesting and transportating techniques should be built.

DEMONSTRATION (15 years)

1. Economical, attractive, long-life, low maintanence total energy systems for residences and buildings with long term storage for fuel or electric power produced by the system, automobiles powered by this fuel or electricity, and recycling of liquid wastes should be developed. The objective would be to demonstrate a system which could become standard for new structures built in the 1990's and beyond.

2. Large scale production of renewable fuels (hydrogen, methane, oils) aimed at virtually elliminating the burning of fossil fuels, which can be better used by the chemical industry, should be pursued.

3. A prototype geosynchronous solar power plant of about 1000 MWe or more using the space shuttle and microwave transmission should be built, if the required technologies are developed by that time.

4. Large scale terrestrial electric power plants of more than 1000 MWe could be built if the economics are proven by the prototypes or solar cell arrays are manufactured very cheaply.

5. An ocean-thermal sea plant producing power, fresh water, chemicals, fertilizers, and minerals should be built with government support if a prototype is successful.

Although the recommendations in each category are listed in order of priority, the development of all these systems should be pursued with vigor. It is recommended also that the government pay the entire cost of the demonstration projects, and then after the plants are built and tested, sell them on an open bid basis. To promote the widespread use of systems which are developed and demonstrated, the government should provide tax credits for the installation of solar energy systems, since they do not deplete nonrenewable resources. An alternative approach is to tax resource depletion and pollution associated with the use of fossil and nuclear fuels.

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