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Technical Report

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TECHNICAL AND ECONOMIC FEASIBILITY OF SOLAR AUGMENTATION FOR BOILER FEEDWATER HEATING IN STEAM-ELECTRIC POWER PLANTS

Final Report

November 1976

Prepared for

ENERGY RESEARCH & DEVELOPMENT ADMINISTRATION
Office of Energy Conservation

Contract No. E(11-1)-2864

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THE BENJAMIN FRANKLIN PARKWAY • PHILADELPHIA, PENNSYLVANIA 19103

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ABSTRACT

This report presents the results of a five-month study on the technical and economic feasibility of augmenting the heating of boiler feedwater in steam-electric power plants by solar energy. The study was confined to investigating the possibility of retrofitting existing oil- or gas-fired steam plants with solar collection systems available now or in the near future. The use of four representative solar collectors was investigated in connection with different methods of single degree of freedom sun-following motions. For all collectors, daily sun-following without seasonal adjustment of tilt was found to be cost-effective. ?

Solar augmentation of boiler feedwater heating does not constitute a cost-effective method of fossil fuel conservation. Under the most favorable conditions, an investment of $1200 or more is required to save one barrel of oil per year. Even if all potentially suitable power plants were equipped with solar augmentation, the resultant saving in oil and gas represents less than one-quarter of one percent of the current U.S. consumption of these fuels.

A national survey of fossil fuel-fired steam-electric plants was conducted as a part of this study, and summary data are presented for each state.

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1. INTRODUCTION

This study was performed under the direction of Mr. William H. Steigelmann, Manager, Energy Engineering Laboratory, by personnel of the Franklin Institute Research Laboratories, assisted by utility personnel. The major contributors were:

Richard Crane, Franklin Institute Research Laboratories
Harold G. Lorsch, Franklin Institute Research Laboratories
Alan Rubin, Franklin Institute Research Laboratories
George Wiedersum, Philadelphia Electric Company
George MacNichol, Philadelphia Electric Company
Douglas Gagen, Baltimore Gas and Electric Company

The Government Technical Monitor for the study was Joseph Joyce of the NASA Lewis Research Center acting on behalf of the ERDA Office of Energy Conservation.

2. SUMMARY

2.1 PROJECT DESCRIPTION

A five-month study was undertaken by The Franklin Institute Research Laboratories for the United States Energy Research and Development Administration, Office of Energy Conservation, to determine the technical and economic feasibility of augmenting the heating of boiler feedwater in steam-electric power plants by solar energy. Coal is not considered to be a critical fuel resource; therefore, the study was confined to retrofitting existing oil- or gas-fired plants with solar collection systems that are presently available or will be available in the near future.

A 200-MW oil-fired plant was chosen as being representative of modern, medium-sized plants. The unit actually analyzed is the Crane Unit No. 2 of the Baltimore Gas and Electric Company. It has a string of six boiler feedwater heaters (Figure A-2). A computerized analysis of this plant was performed to determine the effect of adding solar heat at different feedwater heater locations. The ratio of boiler fuel energy saved to the solar energy added to the feedwater, called the "solar fuel saving efficiency," was found to vary from 8 percent to 67 percent from the lowest to the highest temperature feedwater heater. From a variety of solar feedwater heating schemes investigated, the best one was chosen; it is a straight-through scheme in which the feedwater passes through a solar collector field between two successive feedwater heaters (Figure 3-3).

Initially it had been planned to perform a number of solar analyses in order to determine efficiency and effectiveness of solar collection in various regions of the country. When a preliminary analysis for a plant near Philadelphia, Pennsylvania produced highly unfavorable results, the program plan was modified to an analysis of the most favorable location in the U.S.: Inyokern in the high Mojave desert, 150 miles north of Los Angeles, California.

Four types of solar collectors were investigated: one flat plate collector, two trough collectors, and an evacuated tube collector. Four methods of orienting the collectors were analyzed; two-axis systems, however, were ruled out as being too complicated and too expensive for this application. Detailed costs studies were performed for collector fields of different sizes for each collector type and for each method of orientation. Corresponding analyses were carried out for the solar energy collected during each month of the year at Inyokern by collector type and orientation as a function of collector temperature. These cost and performance calculations were combined with the previously determined "solar fuel saving efficiency" to obtain the cost-effectiveness of saving boiler fuel through solar augmentation of feedwater heating (Figure 3-9).

The potential nation-wide impact on the fuel consumption of the electric power industry was evaluated through a survey of 14 utilities representing 13 percent of the U.S. oil- and gas-fired generation capacity. They were selected on the basis of predominant oil and natural gas use. The suitability for solar retrofit of each of their plants was analyzed on the basis of present fuel use, possibility of conversion to coal, planned retirement age, and space availability for the installation of solar collector fields.

2.2 RESULTS AND CONCLUSIONS

1. Solar augmentation of boiler feedwater heating in steam-electric power does not constitute a cost-effective method of fuel conservation at any location in the coterminous United States. An investment of $1200 or more is required to save one barrel of fuel oil per year. On the basis of $15 per barrel, the investment in a solar augmentation installation at Inyokern, California, the most favorable location in the United States, would earn an annual return of 1.2 percent. For an East Coast location, this return would be approximately one-half as much.

2. If all potentially suitable power plants were equipped with solar augmentation devices, the saving in oil and natural gas consumption would be equal to 0.82×10^{14} Btu per year (0.082 Quads/yr). While this is more than one percent of the electric utility consumption of those fuels, it represents slightly less than one-quarter of one percent of the nation's current use of oil and natural gas.

3. The investment required to achieve this saving is estimated to be $30 billion which is approximately equal to the total investment of the electric power industry during one or two years. This does not include R&D costs or real estate costs.

4. These financial results are relatively insensitive to future reductions in the cost of solar thermal collectors, because these account for only approximately one-quarter of system costs. The bulk of the cost is caused by such conventional items as piping, insulation, support frames, and foundations; no major reductions can be expected in any of these costs. Only the use of concentrating mirrors may offer a significant reduction in solar collection costs.

5. One of the major reasons for the low cost-effectiveness of solar augmentation of feedwater heating is the fact that one Btu of solar energy added to the feedwater results in less than one Btu of boiler fuel energy saved. The ratio of fuel saved to feedwater energy added varies from 8 percent to 90 percent depending on the temperature of the solar energy added; the lower the temperature of solar augmentation, the lower that ratio. In the words of a power plant operator,

   "the turbine extraction steam used to heat low-temperature feedwater is practically worthless; it is sometimes easier to send it through a feedwater heater (and make it do a little work) than to send it through the condenser."

   This contrasts with the utilization of solar energy to space heating where approximately 1.5 Btu of furnace fuel is saved for each Btu of solar energy collected.

6. Another reason for the low cost-effectiveness of solar feedwater heating is the relatively high temperature at which heat must be added to the system. The most cost-effective solar augmentation temperature range is 220°F to 280°F at Inyokern, California; it is slightly lower at locations receiving less insolation. Solar collectors have low efficiencies, at these temperatures.

7. Out of the four collector types investigated, the Northrup (trough) collector is most cost-effective below 250°F, the Corning (evacuated tube) collector is best between 250°F and 400°F, and the CPC (Winston, trough) collector is best above 400°F. The flat plate collector investigated is inferior to these collectors at all temperatures

8. Annual solar collection is relatively insensitive to collector tilt in the north-south direction; with minor exceptions, a fixed tilt angle is most cost-effective for all collector types investigated. Daily rotation to follow the east-west motion of the sun, however, is cost-effective for all collectors.

2.3 RECOMMENDATIONS

1. On the basis of the findings of this study it is recommended that no further work be undertaken on solar augmentation of boiler feedwater heating by means of solar thermal collectors.

2. The feasibility of solar augmentation through concentrating mirrors should be investigated.

3. SOLAR AUGMENTED FEEDWATER HEATING

3.1 INTRODUCTION

Feedwater heaters (FWH) are used at modern steam-electric power plants to raise the temperature of the feedwater as it flows from the condenser to the boiler. A simple regenerative feedwater cycle is shown in Figure 3-1. Steam extracted from the turbine supplies heat to the feedwater heaters. As the steam condenses it gives up heat to the feedwater. The condensate is supercooled in the drain cooler section of one FWH before it flows to the next lower pressure FWH. The series of FWH's is called a "string".

Regenerative cycles significantly improve plant efficiency because, for every 10°F rise in feedwater temperature, there is a reduction of approximately 1% in the heat that must be added in the boiler to make steam. Approximately 30 to 40% of the total boiler steam flow is extracted for feedwater heating. Description of the design, selection, and operation of feedwater heaters may be found in References 1 and 2. References 3 and 4 discuss limitations on plant performance during abnormal conditions such as when one or more FWH's are out of service.

Since feedwater heating occurs at lower temperatures (100°F-500°F) than steam generation (700-1050°F) it appears that solar energy could be used to heat feedwater, thus saving turbine extraction steam and decreasing the plant heat rate — either by increasing low pressure turbine output or by decreasing boiler fuel flow. This method of energy conservation is most attractive as a retrofit to existing oil-or gas-fired steam-electric plants. There are a number of schemes that can be used to augment feedwater heating of an existing steam power plant with solar energy. Four schemes are described below, and the advantages and disadvantages of each are discussed. No attempt was made to perform a detailed design of each scheme, but sufficient analysis was done to conclude that one scheme is definitely superior to the others.

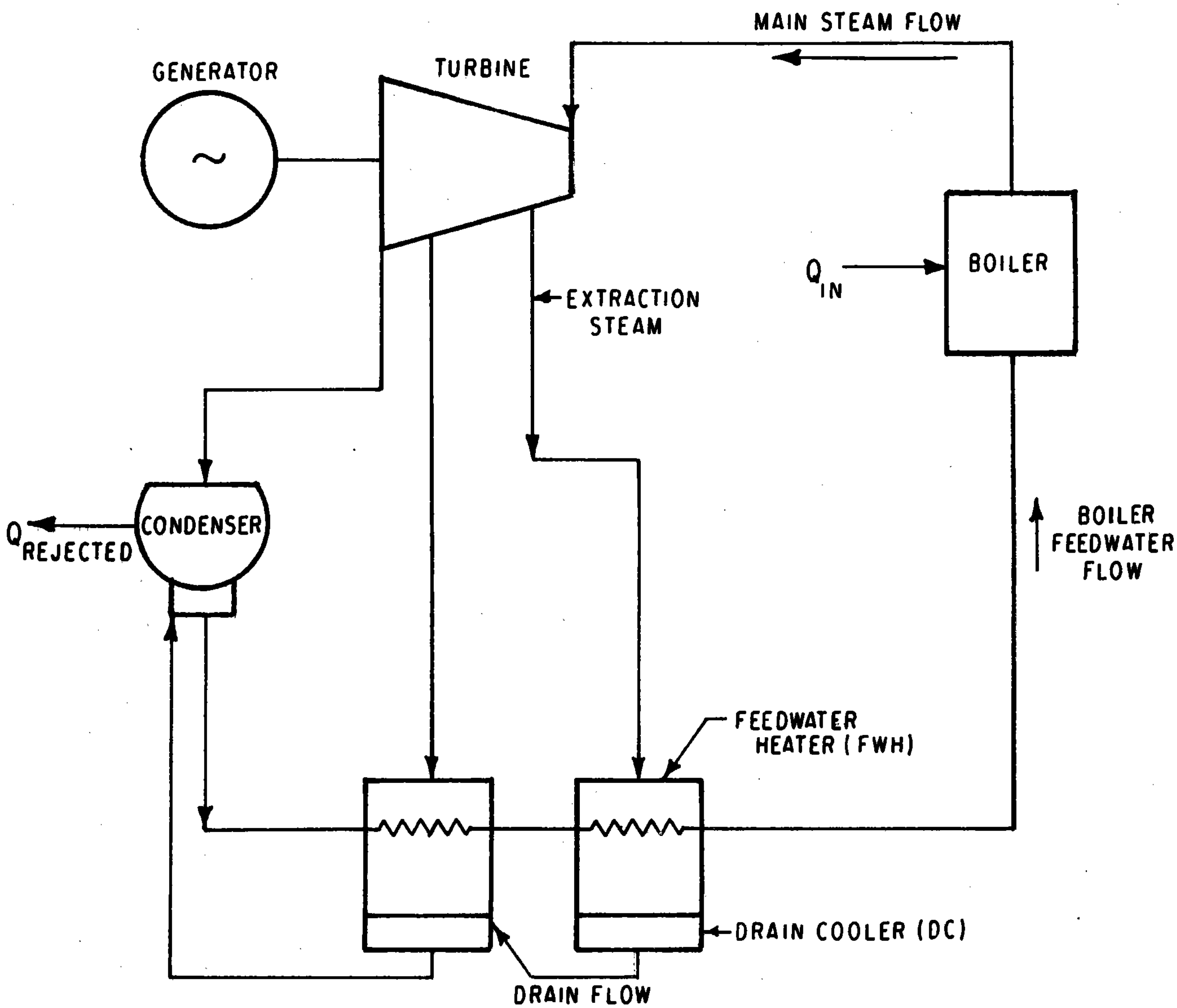

Figure 3-1. Regenerative Feedwater Heating Cycle

3.2 SCHEMES FOR SOLAR AUGMENTED FEEDWATER HEATING

Scheme 1 through 4 are shown schematically in Figures 3-2 through 3-5, respectively. For clarity, these schemes are shown without energy storage, but any of them could include a storage tank also. A discussion of the need for, and the advantages and disadvantages of, energy storage as applied to solar augmented feedwater heating is given in Section 3.3.

Scheme 1. Solar Collector Parallel to Feedwater Heater (Figure 3-2)

Feedwater may either flow through a FWH or through solar collectors and then return to the normal feedwater line downstream of the bypassed feedwater heater. The basic operation of this scheme is as follows: when sufficient solar energy is available, feedwater is directed to the solar collectors, bypassing the FWH; when solar energy is insufficient, the feedwater flows in the conventional manner through the FWH. Control valve "A" can be operated automatically to divert total or partial feedwater flow to the solar collectors depending on the available solar energy. If the total energy normally supplied by extraction steam can be obtained from the sun, all the flow bypasses the FWH. If only a certain fraction of the heat can be collected in the solar collectors, the flow can be regulated so that partial feedwater flow goes through the collectors and the remainder flows in parallel through the FWH. In this method, the amount of steam extracted from the turbine is inversely proportional to the solar energy input and is less than that normally extracted without solar augmentation. The controls required to balance the flow between the collector and the FWH are relatively complex.

Scheme 2. Solar Collector in Series with Feedwater Heater (Figure 3-3)

The operation of this scheme is similar to that of Scheme 1, but the control problem is simplified. On days when solar energy can be collected feedwater is diverted to the solar collectors by valve "A", the flow is then piped back to the normal feedwater line and continues in series through the FWH. The feedwater temperature is controlled automatically because of the self-regulating feature of the FWH (see Section 3.3). If

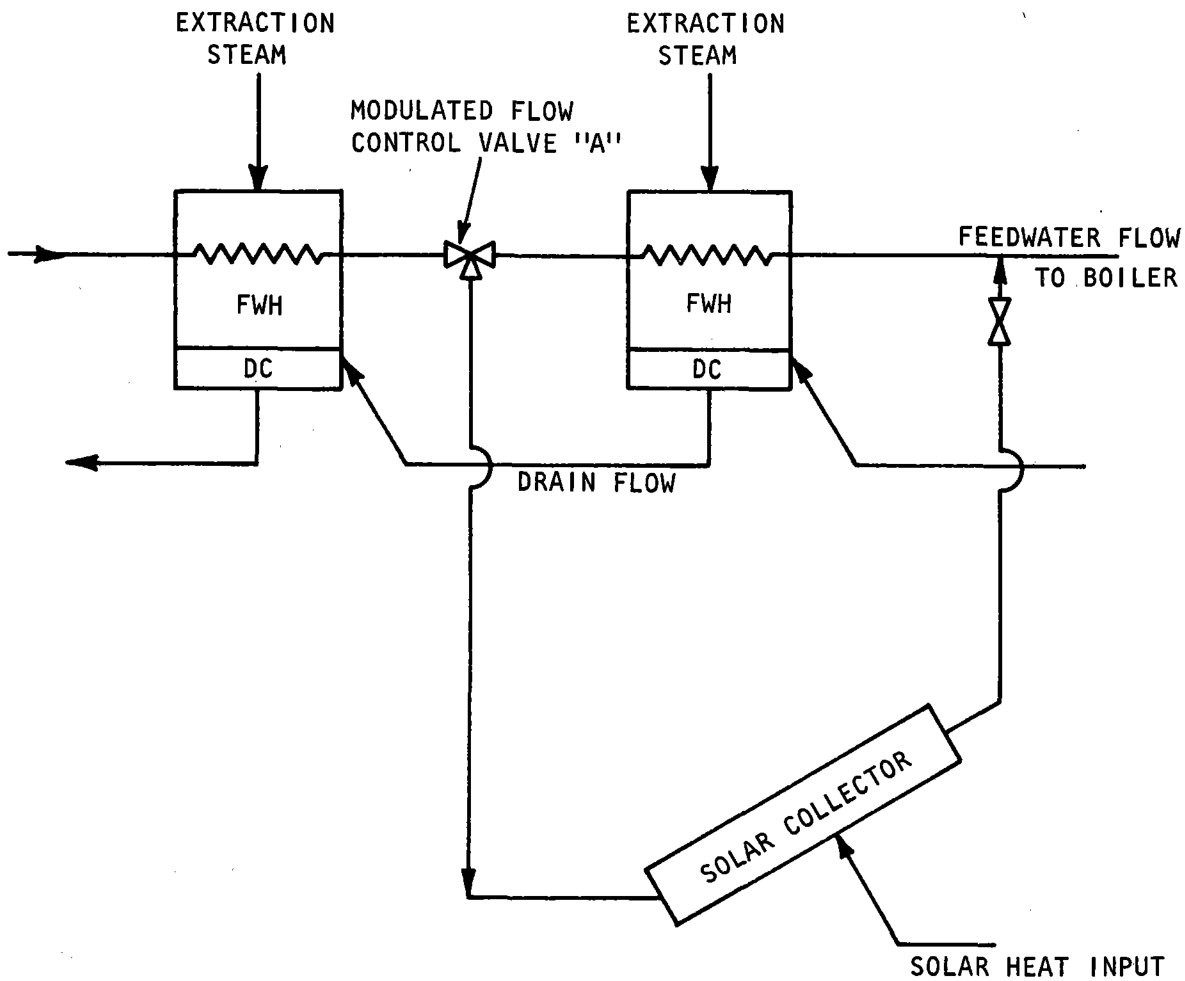

Figure 3-2. Scheme 1, Solar Collector Parallel to Feedwater Heater (for notation, see Figure 3-1)

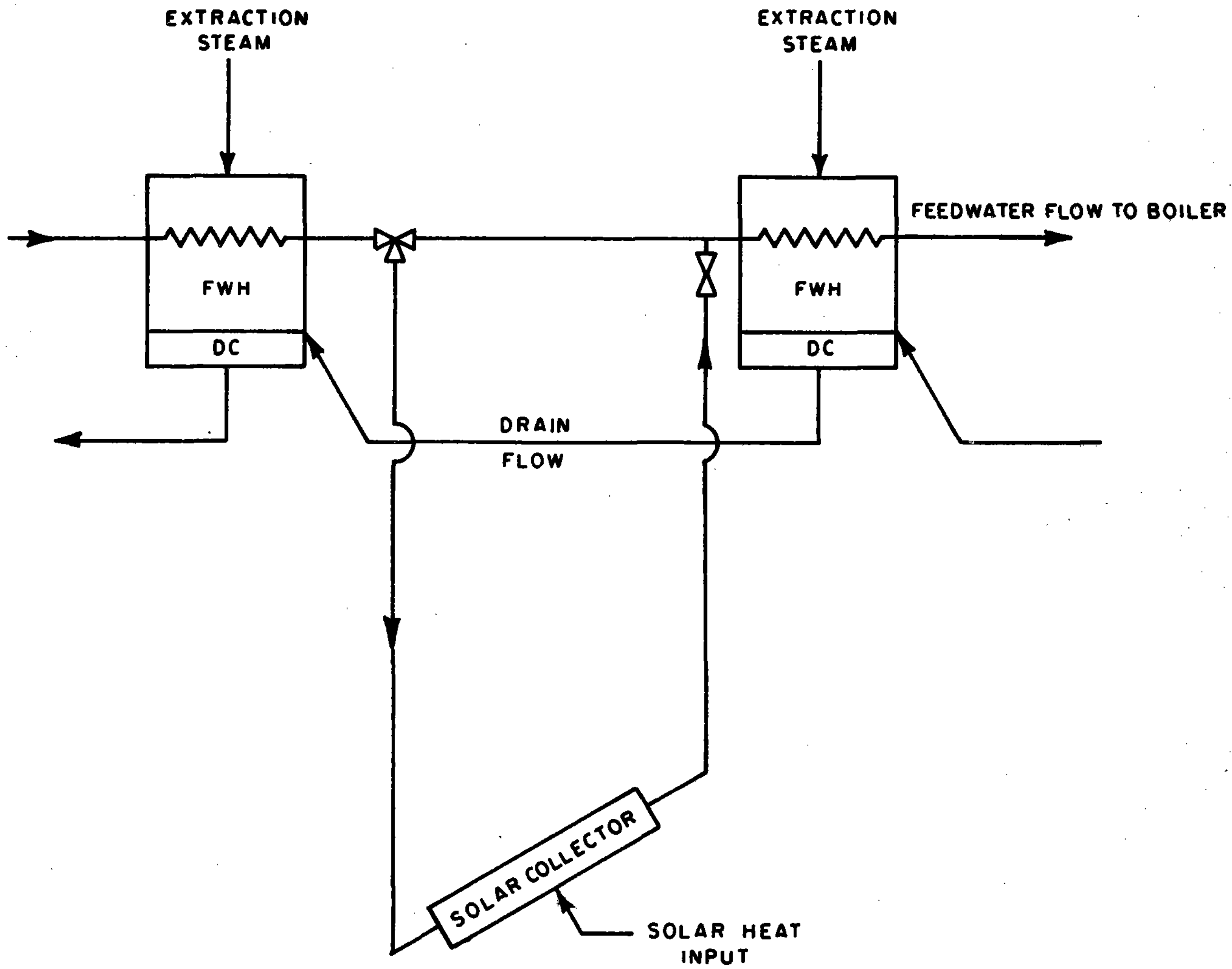

Figure 3-3. Scheme 2, Solar Collector in Series with Feedwater Heater (for notation, see Figure 3-1)

insolation is sufficient to heat the feedwater to its normal design temperature leaving the next higher temperature feedwater heater, no steam is required from the turbine at that extraction point. If only part of the design heat input is supplied by the solar collectors, sufficient steam is extracted to maintain the design terminal temperature difference, TTD (extraction steam inlet saturation temperature minus feedwater outlet temperature). If more solar energy is collected than is normally supplied by the FWH, the extraction steam to the next FWH in the string is reduced. At night, during rainy days, and at other times when there is little or no solar input, the feedwater does not flow through the solar collectors. All the flow passes through the normal piping systems, and the plant operates in a conventional manner.

One disadvantage of this scheme is that, even when no heat is being added in the FWH, feedwater still flows through the heater. Therefore, power is always required to overcome the pressure drop through the tubes. However, even taking this into account, this scheme is preferred over the others because of the simplicity of operation and the minimum number of controls required in a retrofit application.

Scheme 3. Flash Pressurized Hot Water into FWH (Figure 3-4)

In this scheme, the solar collector loop is pressurized, and water is heated in the collectors to the design steam temperature entering the FWH. The hot water flashes into steam as it enters the lower pressure region in the FWH. The flashed steam conditions match the normal extraction steam conditions and thereby reduce or eliminate the need for extraction steam from the turbine. A portion of the drain condensate flows back to the collector to complete the cycle.

An advantage of this scheme is that the mass flow through the collector loop is much lower than the feedwater flow through the loop in Schemes 1 and 2, and therefore the pumping power requirement is reduced. However,

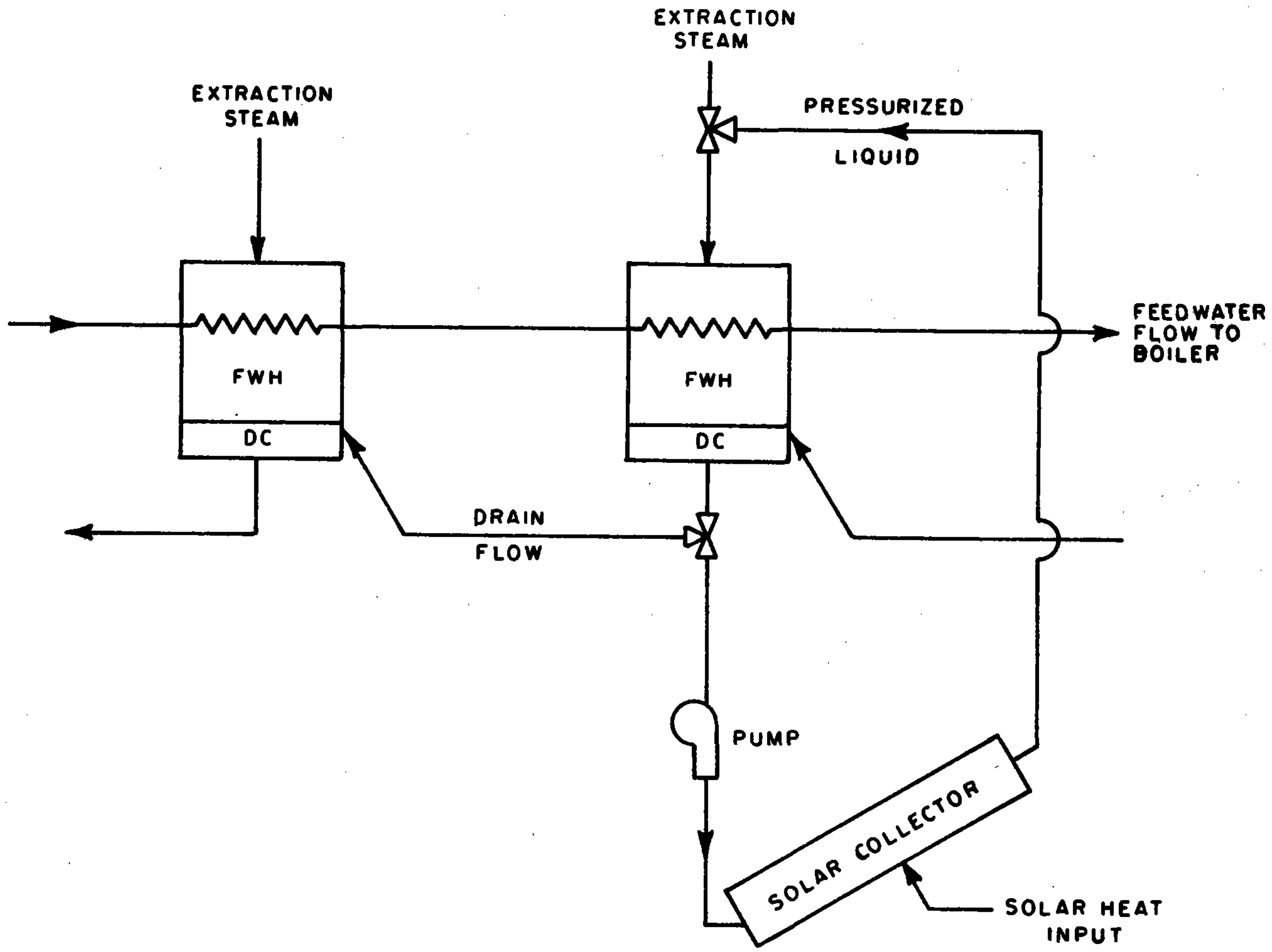

Figure 3-4. Scheme 3, Flash Pressurized Hot Water into Feedwater Heater (for notation, see Figure 3-1)

this scheme is inferior to Scheme 2 because of the following reasons: (1) the pressure in the loop is very high (up to 1000 psi even for intermediate pressure FWH's); therefore high pressure piping is required throughout the collector loop. (2) An additional pump is necessary to pressurize the system. (3) The temperature in the collectors is higher than in the other schemes; therefore the collection efficiency is reduced and more expensive collectors may be required. (4) Steam flow from the solar loop and from the extracting steam lines have to be balanced so that the control system would have to be much more complex than the controls for Scheme 2.

Scheme 4. Heat Condensate Drain Flow (Figure 3-5)

Adding heat to the condensate flow in the solar collectors increases the energy transferred to the feedwater from the drain flow and therefore reduces the requirement for extraction steam to maintain the design TTD. This is a less direct method to reduce extraction steam flow than Schemes 1 through 3.

The advantages of this scheme are: (1) few or no controls are required because of the self-regulating operation of the FWH, and (2) the mass flow through the collector and therefore the pumping requirements for the system are less than that for Schemes 1 and 2. The scheme, however, is probably not feasible on a retrofit application because of the limitation in allowable temperature rise of the drain flow. If the water temperature were raised significantly, the pressure in the drain lines would generally not be high enough to prevent water from flashing in the pipes. Even without solar augmentation, flashing in drain lines has been a problem in some existing power plants, and schemes conducive to that condition are therefore undesirable.

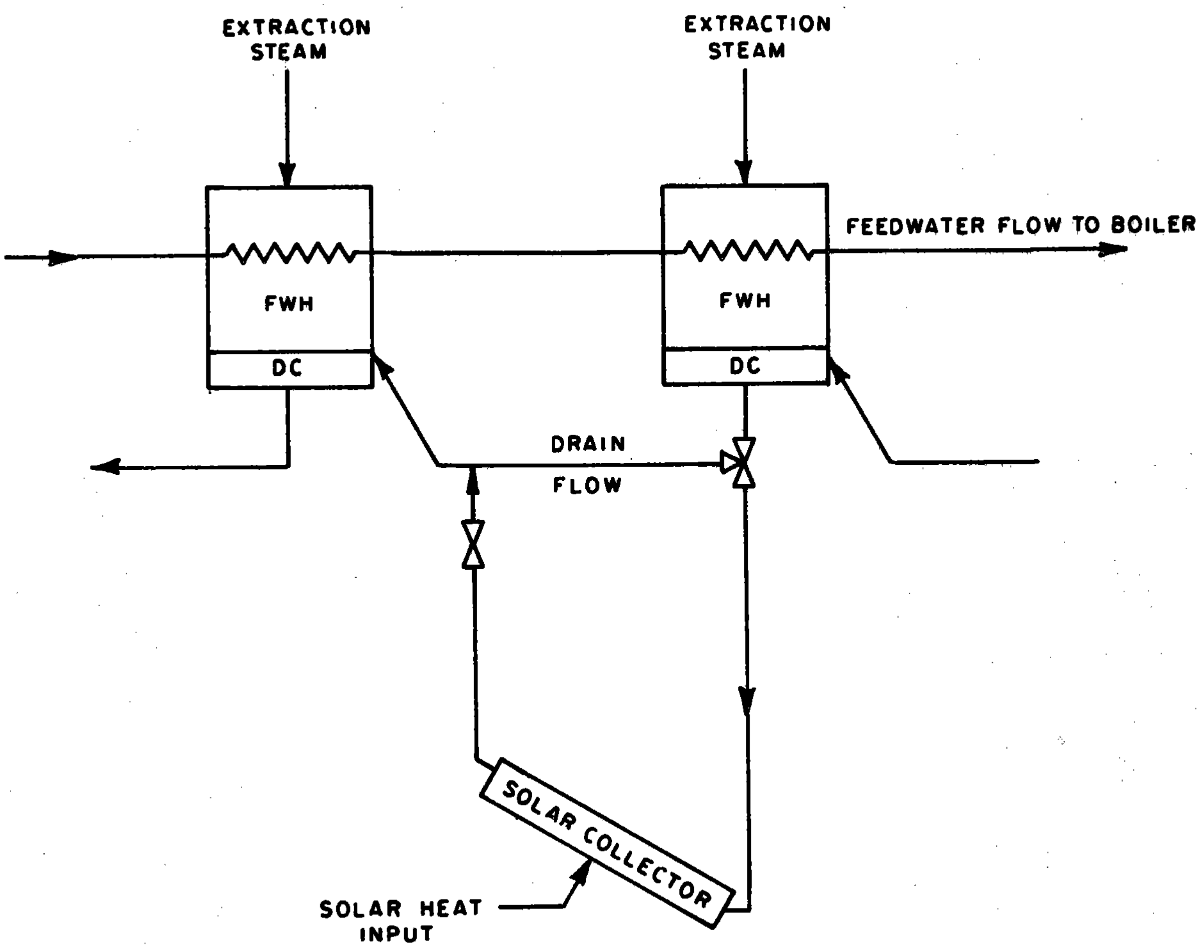

Figure 3-5. Scheme 4, Heat Condensate Drain Flow (for notation, see Figure 3-1)

3.3 ENERGY STORAGE

A storage tank may be used in connection with solar augmented feedwater heating systems. A typical installation with a storage tank is depicted schematically in Figure 3-6. Thermal energy from the solar collectors is transferred to the storage tank by a separate flow loop. Heat is then transferred to the feedwater through a heat exchanger in the tank. There are several disadvantages to using a storage tank: (1) the additional complexities and required capital expense for the tank, heat exchanger, pump, and controls, (2) loss of efficiency due to an additional temperature drop across the heat exchanger, and (3) additional energy required to pump liquid around the solar collector loop. Therefore, the use of a storage tank should be avoided if possible.

Initially, it was believed that storage might be required as a buffer to reduce the effect of thermal transients during times when the sun is covered by passing clouds. However, this turned out to be unnecessary because of two reasons: (1) there is sufficient thermal inertia in the system to prevent rapid changes in feedwater temperatures and (2) more important, any change in feedwater temperature due to fluctuation in solar energy input is compensated in the next FWH in the string because feedwater heaters are self-regulating. For example, if the feedwater temperature decreased, the saturation temperature and pressure in the FWH would also drop. This would cause an increased flow of extraction steam from the turbine to the FWH which in turn, would input more energy to the feedwater. Correspondingly, an increase in feedwater temperature to the FWH would raise the saturation pressure and reduce extraction steam flow. Feedwater heaters are designed to maintain a certain terminal temperature difference. In a conventional plant, if one FWH is out of service for maintenance or another reason, the extraction steam to the next FWH is approximately doubled to try to maintain the design TTD. In a modified plant with solar augmentation, changes in feedwater temperature due to fluctuation in solar energy input would automatically be compensated in

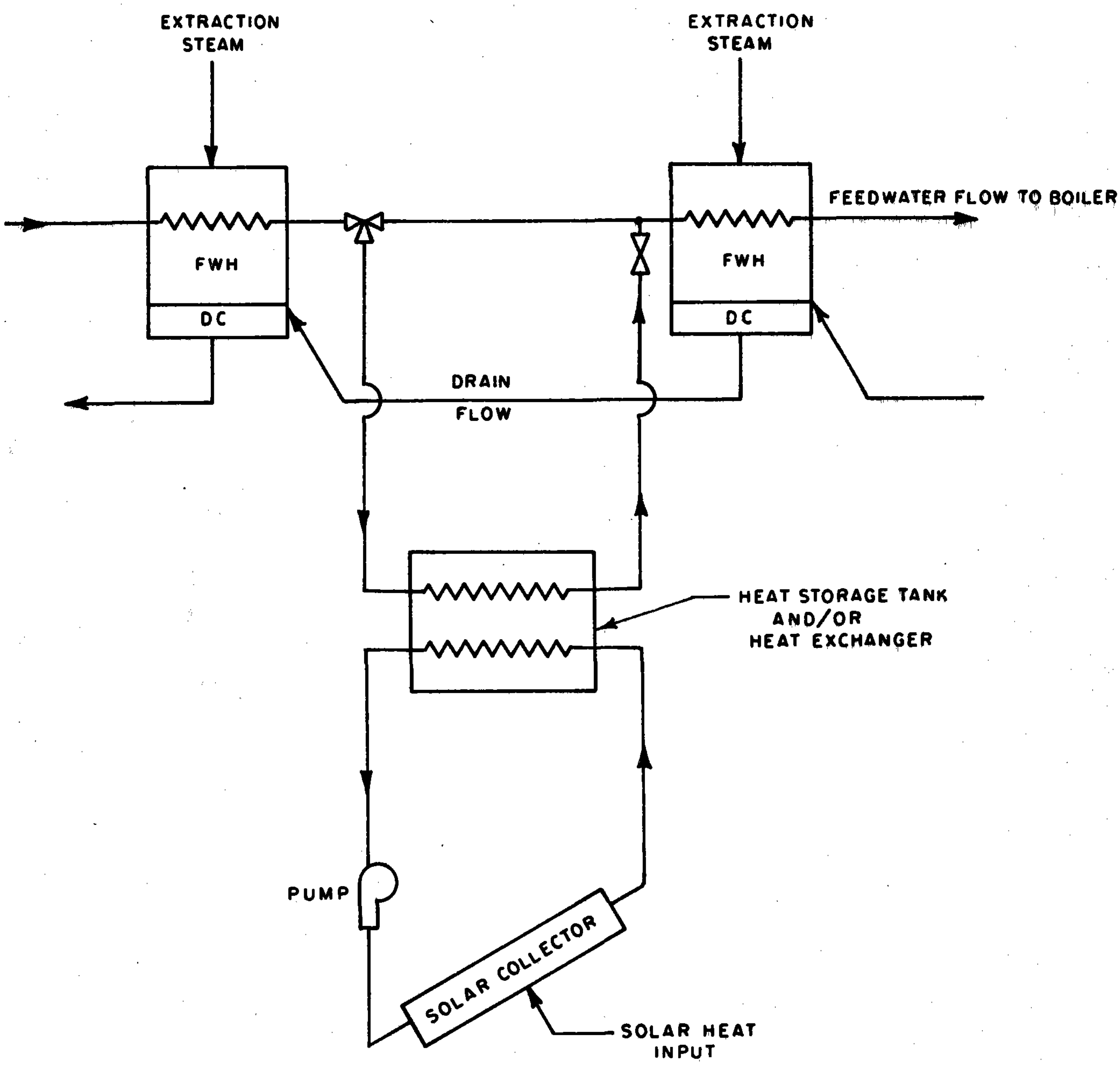

Figure 3-6. Solar-Augmented Feedwater Heating with Heat Storage Tank and/or Heat Exchanger.

the feedwater heating string so that plant performance would not be significantly affected (except for changes in heat rate). Therefore, a storage tank is not required as a buffer against temperature variations.

If the pressure in the feedwater line is much greater than the saturation pressure corresponding to the feedwater temperature, it is economical to separate the feedwater and the solar collector loops with a storage tank/heat exchanger and to have a lower pressure in the solar collector loop than in the feedwater loop. This avoids the need to install high pressure pipes throughout the solar collector field. This situation occurs, for the most part, after the high pressure feedwater pump which raises the pressure in the feedwater line from approximately 200 psi to approximately 2700 psi (Figure A-2). The saturation pressure corresponding to the maximum feedwater temperature entering the boiler is generally less than 700 psi which is much less than the 2700 psia pressure in the feedwater line. For example, a temperature of 500°F corresponds to a saturation pressure of 680 psia.

In addition to a consideration of pressure, the feedwater temperature downstream of the high pressure pump is generally greater than 300°F. Therefore, more expensive solar collectors are required for solar augmentation at the high pressure heater end than at the low or intermediate pressure FWH's.

Since, from an energy conservation point of view, it does not matter when a barrel of oil is saved, there is no need for an energy storage system to utilize solar energy at specific times of the day. There may be cases in which a storage tank is required, however. Only if solar energy cannot be utilized at the time when it is available does energy storage provide additional fuel savings. This might happen, for example, when a plant is down for maintenance or repair and the sun is shining. This is not considered to be a regular occurrence, and therefore it is not economical to install a storage system for such situations.

Energy storage would provide additional fuel savings at other times when collectible solar energy could not otherwise be utilized. During sunny summer afternoons, the demand for electrical energy is high, and many plants operate at their maximum output. If the plant were already operating at the maximum flow condition, solar augmented feedwater heating would reduce steam extraction flow and thereby increase steam flow in the low pressure turbine beyond the recommended limit. Hence, because of the limitation, solar augmentation will not work in this situation.

Four remedies exist to correct this situation. The simplest one is not to use solar energy during such times. This might be satisfactory if the situation did not occur often. An analysis of the operation of each plant would be required to determine the suitability of this solution.

Another possibility is to install an energy storage system. When plant output is at a peak and the sun is shining, solar energy could be stored for use at a later time such as in the evening when plant output is reduced and turbine steam flow is not a limiting factor. This would permit the solar energy to be stored and used during off-peak hours for energy conservation.

A third alternative is to utilize the solar energy when it is available, even when the plant is operating at maximum output conditions. This would reduce extraction steam from the turbine at some point, and would therefore require that the steam flow be throttled to limit the flow at the low pressure end to the maximum calculated flow. Since steam flow would be reduced through the high pressure turbine and possibly through portions of the intermediate pressure turbines, the net result would be a reduction in plant output, but an improvement in heat rate. This may not be an ideal situation during a period of peak demand because, even though fuel is conserved with solar augmentation at one plant, the utility must make up for this reduction in electric generation by increasing the generation at other plants. Depending on the utility system, this may require increased output from less efficient peaking units (i.e. gas turbines, or older steam-electric plants) and little or no overall energy conservation.

A fourth alternative exists because of the possibility of increased turbine capability. Turbine manufacturers generally rate their turbines at three conditions - (1) maximum guaranteed, (2) maximum calculated (or valves wide open), and (3) 5-percent overpressure. The plant performance (heat rate) is guaranteed at the first condition only. Utilities generally consider this an acceptable plant operating condition for 10 to 12 hours per day. Using the maximum guaranteed heat balance as a reference, steam flows at the maximum calculated condition are approximately 105 percent of the flows at the maximum guaranteed condition. For plants with equipment in relatively good condition, this flow is attainable continuously for hours at a time, but the plant heat rate is slightly higher than that for the maximum guaranteed flow. To attain the 5-percent overpressure condition, valves are wide open, additional steam flows through the boiler, and the main steam pressure is raised by 5 percent over the maximum guaranteed condition. The results is a steam flow of approximately 110 percent of the maximum guaranteed flow. The 5-percent overpressure condition is generally considered by utilities as an emergencey rating such as during peak periods when other capacity is not available. A plant would not be run at that condition for more than a few hours at a time. Excessive operation at this condition would significantly shorten the life expectancy of plant equipment.

Therefore, depending on whether the plant load is the maximum guaranteed or the maximum calculated, potential flow conditions may be either 105 percent or 110 percent of normal full load conditions. In plants with additional capacity, energy storage is not required for solar and augmented feedwater heating.

Discussions with turbine manufacturers have led us to conclude that, unless detailed analyses of heat balances and steam flows are done on existing units on a plant-by-plant basis to determine whether or not the turbine has excess capacity, the recommended procedure is to limit the steam flow out of the low pressure end of the turbine to the maximum calculated flow. Such a study was not within the scope of this program. This analysis assumes storage is not required. If energy storage were included, the cost of the solar augmented system would increase.

3.4 INSTALLATION DOWN-TIME

An estimate of the down-time required to retrofit a power plant with the solar-augmented feedwater heating scheme shown in Figure 3-3 was obtained from Philadelphia Electric Company. It was assumed that, with the exception of the final connection to the feedwater line, the entire solar collector array and associated piping can be installed without disrupting normal plant operation. The final connection requires cutting into the existing feedwater line and installing two tees and valves. The pipe, which is approximately 16 inches in diameter, must be cut and re-welded. If the system were installed downstream of the high pressure feedwater pump where the pressure is approximately 3,000 psi, more involved preparation, welding, and heat treatment would be required than if an installation were made on the low pressure (less than 500 psi) feedwater heaters. With proper planning, the plant down-time would be from two days to a maximum of one week. Usually, this could be worked into a normal plant outage.

Larger new plants may have two parallel strings of feedwater heaters. In these plants, one string of heaters can be cut out for several days in order to install the solar augmented system. When this is done the plant load must be reduced by about 50 percent.

In general, it is felt that the down-time for retrofitting an existing plant with solar augmented feedwater heating is minimal and would not be a barrier to the implementation of this concept.

3.5 ENERGY AND COST ANALYSIS

A basic feedwater heating cycle is shown in Figure 3-1. Methods of augmenting feedwater heating by solar energy are treated in Section 3.2. The ratios of fuel energy saved to solar energy utilized are derived for different feedwater heater locations in Appendix A. Suitable solar collection systems are described and analyzed in Appendix B. The above components are synthesized in this section which describes an energy analysis for a solar feedwater heating system.

In order to determine the optimum location for the addition of solar energy to the feedwater heating system, a typical oil-fired modern power plant was analyzed. It is the Crane Unit No. 2 of the Baltimore Gas and Electric Company, The basic thermal cycle of that plant is shown in Figure A-2 of Appendix A. A computer program developed jointly by that utility and the Philadelphia Electric Company was used to determine the fuel saving efficiency of solar augmentation; i.e., the amount of boiler fuel energy saved for each unit of solar energy added to the boiler feedwater at various temperatures. The results of this analysis are summarized in Table 3-1; a full description is given in Appendix A.

Table 3-1. Fuel Saving Efficiency of Solar Augmentation

Solar Heat Input		Fuel Saving Efficiency (%)
Location	Temperature °F	
Before FWH #1	130	8
Before FWH #2	200	32
Before FWH #3	270	49
Before FWH #4	325	53
Before FWH #5	395	64
Before FWH #6	455	67

*Notes: FWH denotes Feedwater Heater.
For locations and FWH temperatures, see Figure A-2, page A-5.

Four solar collectors suitable for boiler feedwater heating were investigated, they are:

- Chamberlain, a high performance flat plate collector with a selective, black absorber coating [17],
- Corning, an evacuated tube collector [18],
- CPC, the compound parabolic concentrator, also known as the Winston collector, which is a non-imaging concentrator consisting of north-south troughs with parabolic walls [19], and
- Northrup, a concentrating collector consisting of north-south troughs with straight walls and a curved Fresnel lens at the top; the troughs rotate to follow the daily motion of the sun [20].

These collectors are described more fully in Section B-1 of Appendix B. They are representative of the type of collectors available today or in the near future.

Four methods of orientation were investigated for the solar collectors. They are:

- fixed,
- tilt angle adjusted monthly,
- fixed, tilted axis about which the collector rotates to follow the daily motion of the sun,
- same, but the tilt of the axis of rotation is adjusted monthly.

These methods are described more fully in Section B-2 of Appendix B.

Depending on geographical location, the amount of energy that can be collected by a collector field of a given size varies greatly throughout the United States. At the start of the project it was planned to perform a detailed analysis for solar augmentation of a power plant of the Philadelphia Electric Company located in or near that city. It soon became apparent that solar augmentation of boiler feedwater heating in the Philadelphia, PA area was entirely unfeasible from an economic point of view. Since no useful purpose would be served by determining the degree of unfeasibility accurately, the project plan was changed toward the determination of feasibility in a most favorable U.S. location.

Based on an Aerospace Corporation study performed for the National Science Foundation during 1973, [Ref. 5], a location in the California Mojave desert near Inyokern, approximately 150 miles north of Los Angeles, is favorable for solar power generation. It would therefore also be favorable for solar augmentation of boiler feedwater heating. According to the Climatic Atlas of the U.S. [Ref. 6], the average daily total insolation on a horizontal surface at Inyokern is 568 langley/day (1 langley = 1 cal/cm^2) or 2090 Btu/ft.^{2} day. Complete weather and solar data are available for Inyokern from the Climatic Data Center of NOAA providing an accurate base for the required calculations. An analysis of solar feedwater heating was therefore undertaken at that location as being representative of optimum conditions for the United States.

The amount of energy that can be collected per ft^2 of collector per year at Inyokern at different temperatures was calculated for each collector and for each method of orientation. These calculations are presented in Section B-3 and are graphically illustrated in Figures B-8 and B-9 of Appendix B.

Costs of the entire solar augmentation system were then estimated for each collector type and for each orientation method for different collector field sizes. The effect of size on cost was within the limits of accuracy of the cost analysis; therefore all cost figures used were calculated for a field of 104,000 square feet. They are summarized in Table 3-2; additional information is presented in Section B-4 of Appendix B. Two sets of unit costs are shown. The higher cost figures on the left of each column represent system costs for high-pressure collector fields, while the lower cost figures on the right of each column in parentheses represent system costs for low-pressure collector fields. The dividing line between the two systems is the feedwater pump which raises the feedwater pressure from ∿200 psi to ∿3000 psi (see Figure A-2, Appendix A). It operates at a temperature of 354/360°F.

Therefore, in practice, that collector temperature constitutes the limit between low-pressure pipe and high-pressure pipe.

Table 3-2. Unit Cost Summary for Solar Augmentation Using Different Collectors and Orientation Methods (dollars per ft^2 of collector)

Collector Tilt Axis		Fixed	Adjusted Monthly	Fixed	Adjusted Monthly
Collector Rotation About Tilt Axis		None	None	Daily	Daily
Collector Type	Unit Cost				
Chamberlain	12	43 (36)	51 (44)	57 (50)	63 (56)
CPC	25	56 (49)	64 (57)	70 (63)	76 (69)
Corning	30	61 (54)	69 (62)	75 (68)	81 (74)
Northrup	14	-	-	45 (38)	53 (46)

Numbers to the left are for high-pressure systems, numbers in parentheses to the right are for low-pressure systems (<200 psi).

The steam cycle shown in Figure A-2 pertains, of course, to a particular power plant. However, it is fairly representative of modern, medium-size (200 MW) steam-electric plants. For any given plant, the break between high and low pressure may occur at a different temperature. However, it will be shown later that solar augmentation at high pressure is economically inferior to low-pressure augmentation; therefore, the exact dividing line between high and low pressure does not affect the final results.

Combining the data on energy collection per ft^2 of collector and the system costs per ft^2 of collector, the capital investment required to collect one million Btu of solar energy per year at Inyokern was determined. It depends on the average collection temperature, the collector type, and the method of collector orientation. The results of these calculations are shown in Figures 3-7 and 3-8 for fixed and daily rotating collectors, respectively.

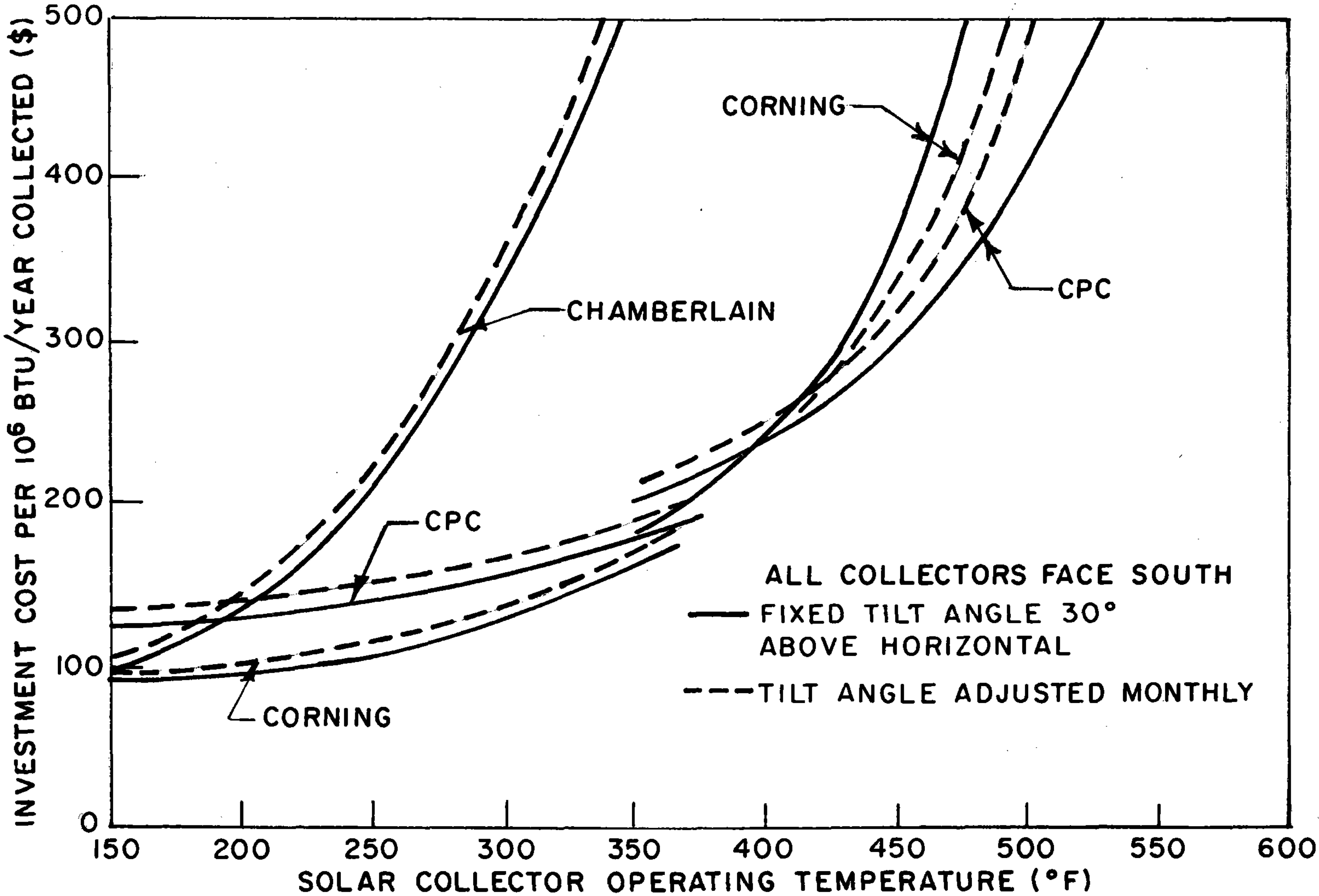

Figure 3-7. Investment Cost Required to Collect 10^6 Btu of Solar Energy per Year at Inyokern, CA as a Function of Collector Temperature. South Facing Collectors.

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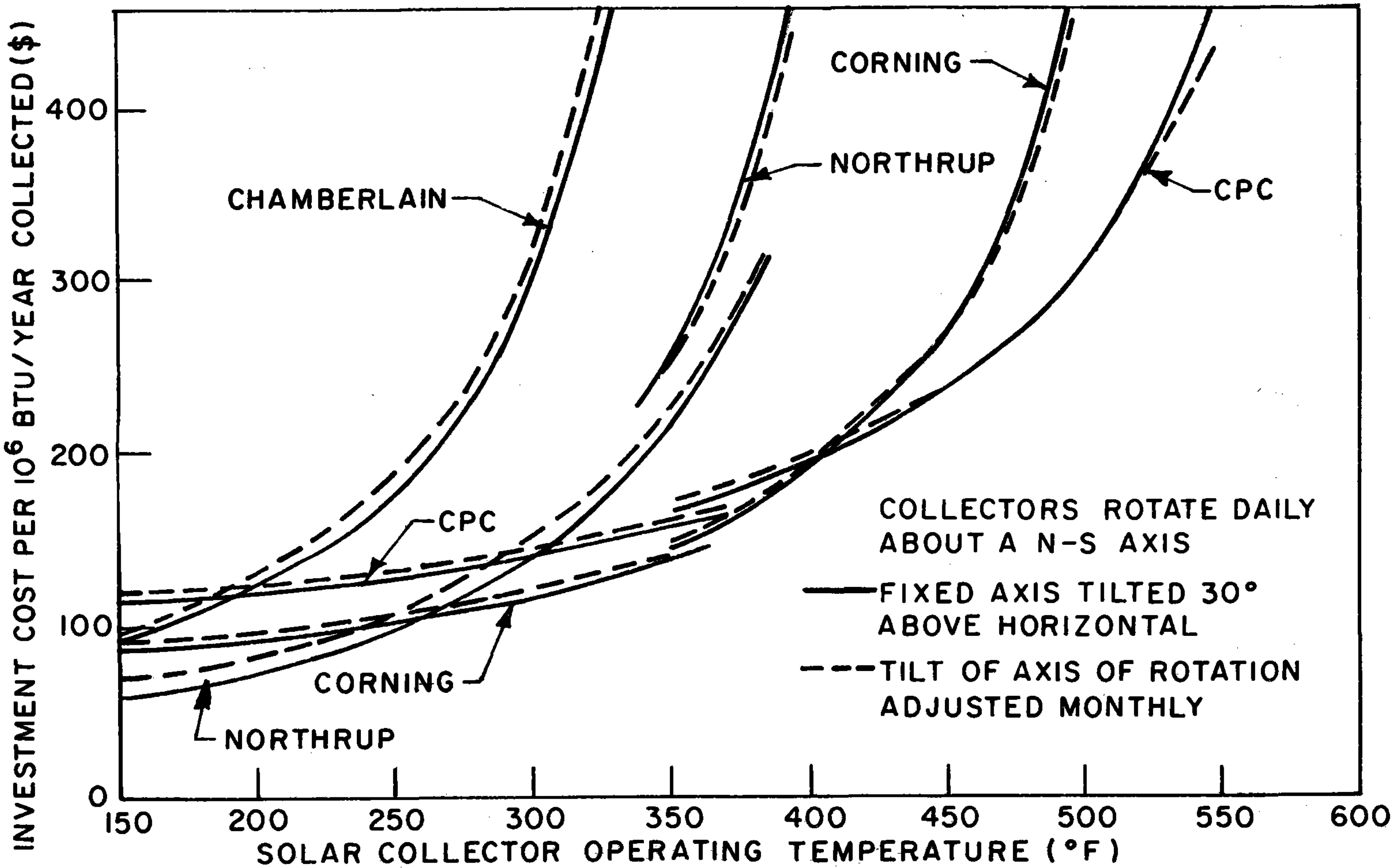

Figure 3-8. Investment Cost Required to Collect 10^6 Btu of Solar Energy per Year at Inyokern, CA as a Function of Collector Temperature. Rotating Collectors.

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Comparing the costs for fixed tilt (solid lines) and monthly adjusted tilt angles (dashed lines) in each figure separately, it becomes apparent that, with minor exceptions, the monthly tilt adjustment is not economically justified for any collector or any east-west orientation method. The major exception is the non-rotating Corning collector at temperatures higher than 400°F. Minor exceptions occur for daily rotating collectors in some temperature regimes; however, the cost differences between collectors having fixed or adjustable axes of rotation is so small as to be well within the accuracy of the calculations. On account of its greater simplicity, the fixed axis is preferable under those conditions, too.

The Chamberlain collector is competitive below 200°F only. At higher temperatures, this flat plate collector is (and probably all flat plate collectors are) more expensive than any other collector furnishing an equal amount of energy. The Northrup collector is most cost effective below 250°F, the CPC collector above 400°F, and the Corning collector appears best for the intermediate range.

Figures 3-7 and 3-8 pertain to collected solar energy only. Table 3-1 must be used to relate the solar augmentation energy to the amount of fuel energy saved. The results are shown in Figure 3-9 which relates capital investment and boiler fuel savings at Inyokern to the temperature at which solar energy is added to the feedwater. Barrels of fuel oil per year has been used as a measure of the fossil fuel saving, but an equivalent amount at natural gas could be substituted. While each collector type used with each orientation method has its own optimum augmentation temperature, certain general conclusions can be drawn.

- For all collectors, daily east-west rotation is more cost-effective than a fixed position. This explains the good performance of the Northrup collector previously noted.
- The optimum temperature for the Chamberlain collector is 215°F but, even at that temperature, this flat plate collector is less cost-effective than any other collector type.

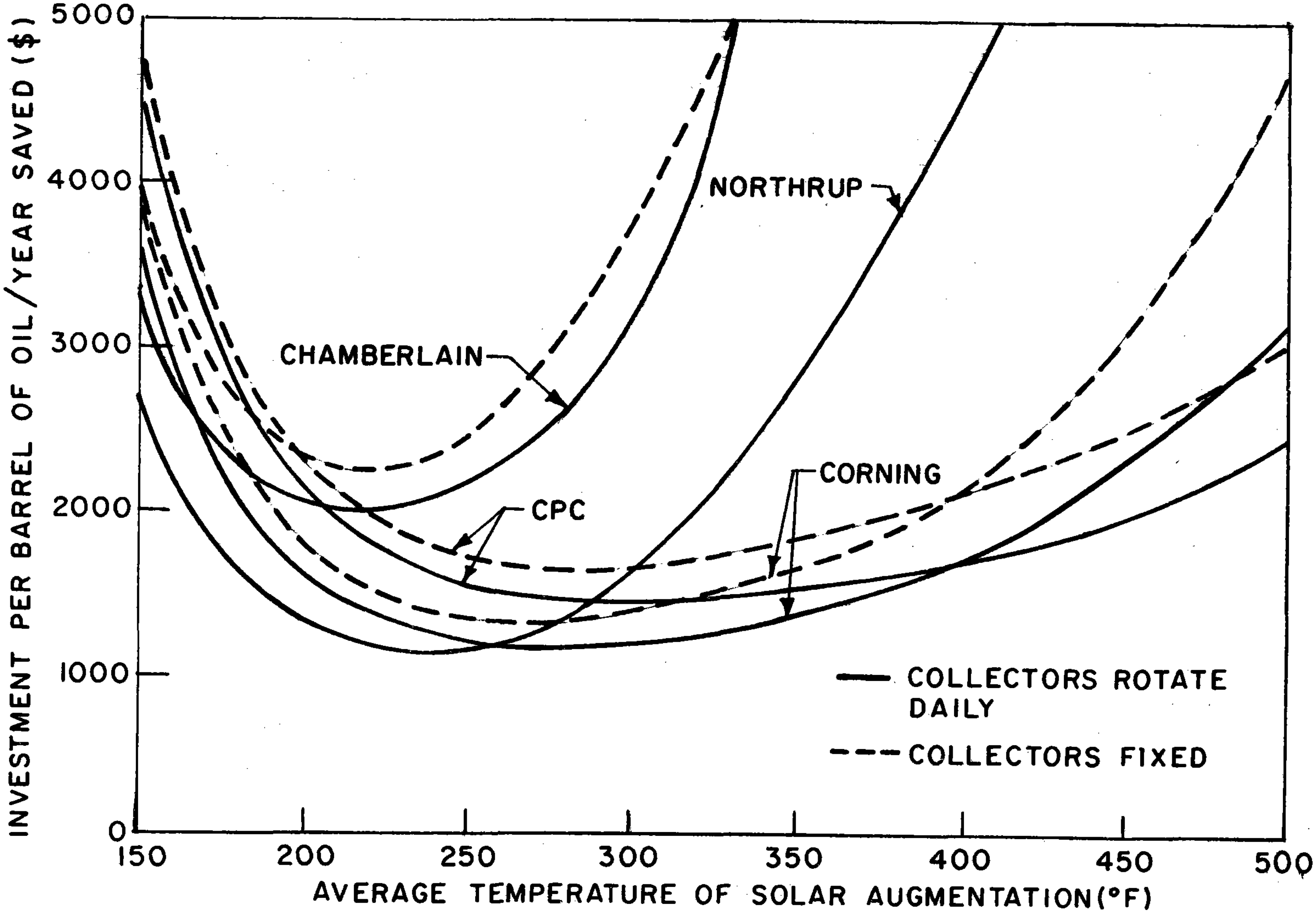

Figure 3-9. Investment Cost Required to Save One Barrel of Oil per Year at Inyokern, CA as a Function of Solar Augmentation Temperature.

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- The Northrup collector is most cost-effective below 250°F, the Corning collector between 250°F and 400°F, and the CPC collector above 400°F.
- The optimum temperature for solar augmentation occurs between 220°F and 280°F with fuel saving efficiencies in the 45% to 50% range. Through that temperature range, it requires a capital investment of more than $1200 to save one barrel of boiler fuel per year.
- At a cost of $15 per barrel, this represents a return on investment of 1.2 percent per year. Even with a drastic rise in the cost of fuel oil, it does not appear that solar augmentation of feedwater heating can become economically justified in the foreseeable future.
- All the above results and conclusions are based on a steam-electric plant located at Inyokern, CA. Since this is a near-optimum location for solar augmentation in the United States, the technical and economic performance of this system would be less favorable at other locations.

4. IMPACT ON ENERGY CONSERVATION

4.1 GEOGRAPHIC VARIATION OF SOLAR ENERGY AVAILABILITY

The availability of solar radiation received on the ground varies significantly from one geographic location to another. A map of the United States is shown in Figure 4-1 on which lines of equal intensity of mean daily solar radiation on a horizontal surface (isopleths) have been drawn. The values indicated are in langleys; 1 langley equals one calorie per square centimeter or 3.69 Btu/ft^2 or 116 J/m^2. The solid lines represent total radiation [Ref. 6] and the dashed lines direct radiation [Ref. 7]. Direct radiation is the beam radiation transmitted from the solar disk to the ground. Total radiation consists of the sum of direct radiation and diffuse radiation, where diffuse radiation is the radiation from the sky due to the scattering of solar radiation. The Southwest has the highest direct and total radiation intensities, while the northeastern and northwestern sections of the country have the lowest.

The amount of solar radiation received on a <u>clear</u> day in the United States is relatively independent of location. It is the number of cloudy and partly cloudy days which determines the mean daily radiation for a given region. While such factors as clearness of the atmosphere, latitude, and altitude have a minor effect on the amount of solar radiation received on the ground, the major effect is from cloud cover. Therefore, the southwestern and southeastern sections of the country, which are noted for having a high percentage of clear days, have the highest values of mean solar radiation.

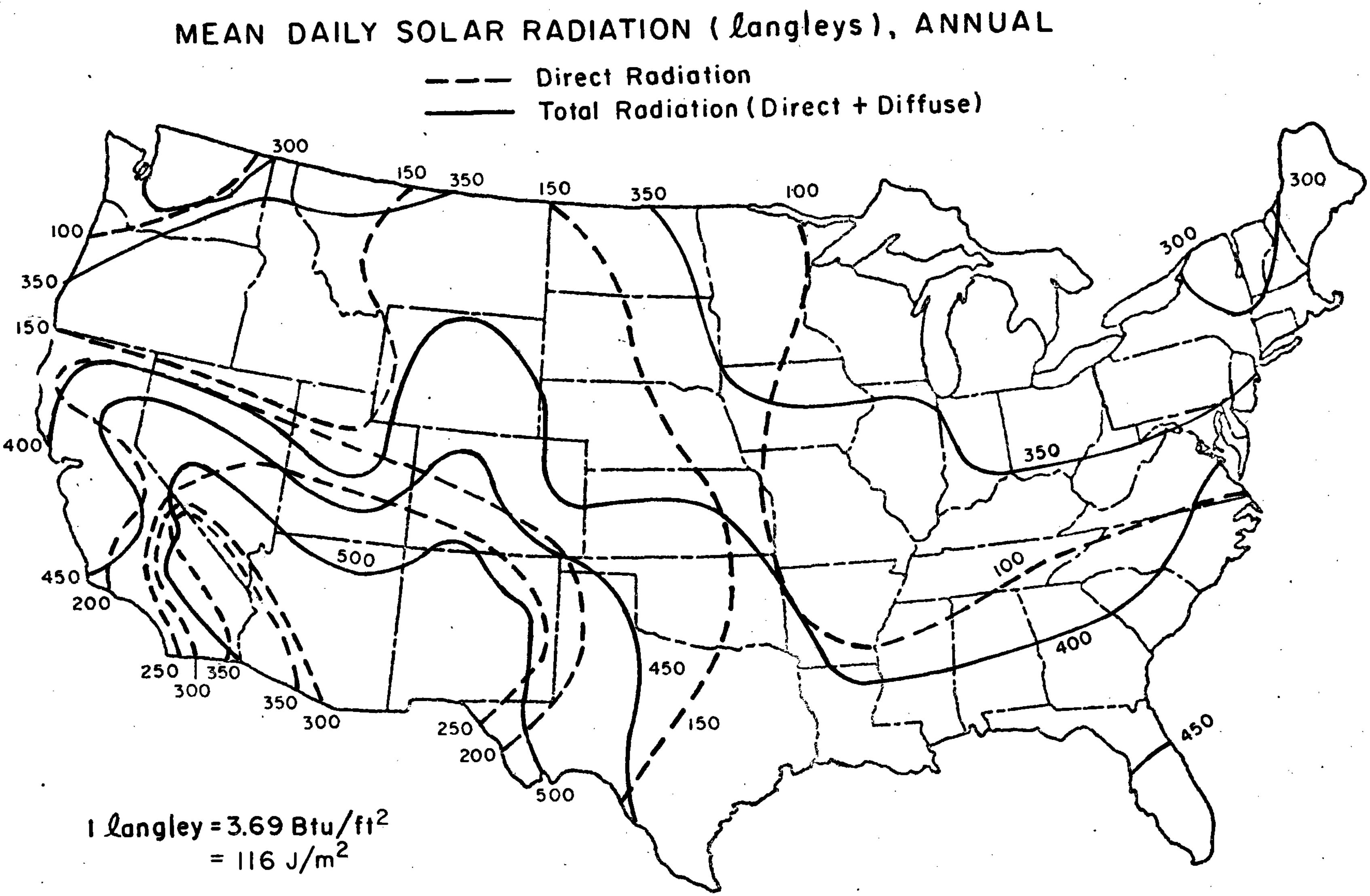

Figure 4-1. Direct and Total Solar Radiation Throughout the U.S.

The technical and economic feasibility of solar energy utilization is directly related to the availability of solar energy. In Figure 4-2, the United States has been divided into four regions based on mean daily total solar radiation:

Region 1: less than 350 langleys
Region 2: 350 to 400 langleys
Region 3: 400 to 450 langleys
Region 4: greater than 450 langleys

(one langley equals 3.69 Btu/ft^2 or 116 J/m^2)

Boundaries between the regions were slightly shifted to make them coincide with state boundaries.

The most cost-effective application of solar feedwater heating will occur in Region 4. Since that region exhibits not only the highest total solar radiation but also the highest ratio of direct to total radiation, the use of concentrating collectors (see Appendix B) will be most advantageous in Region 4.

4.2 NATIONAL INVENTORY OF GAS- AND OIL-FIRED STEAM-ELECTRIC PLANTS

In order to estimate the potential local and national impact on petroleum and natural gas conservation from solar augmented feedwater heating, data were collected on the size and location of all gas- and oil-fired steam-electric generating stations in the U. S. Also included were data on the annual consumption of oil and gas and net generation of electricity for each plant for the year 1974. This information, together with information on solar energy availability, is useful in order to assess the potential impact of the solar-assisted feedwater concept.

Data on steam-electric power plants are presented on a state-by-state basis in Table 4-1. The table is based on 1974 data [Ref. 8], organized by regions in accordance with Figure 4-2. A summary of this information is given in Table 4-2.

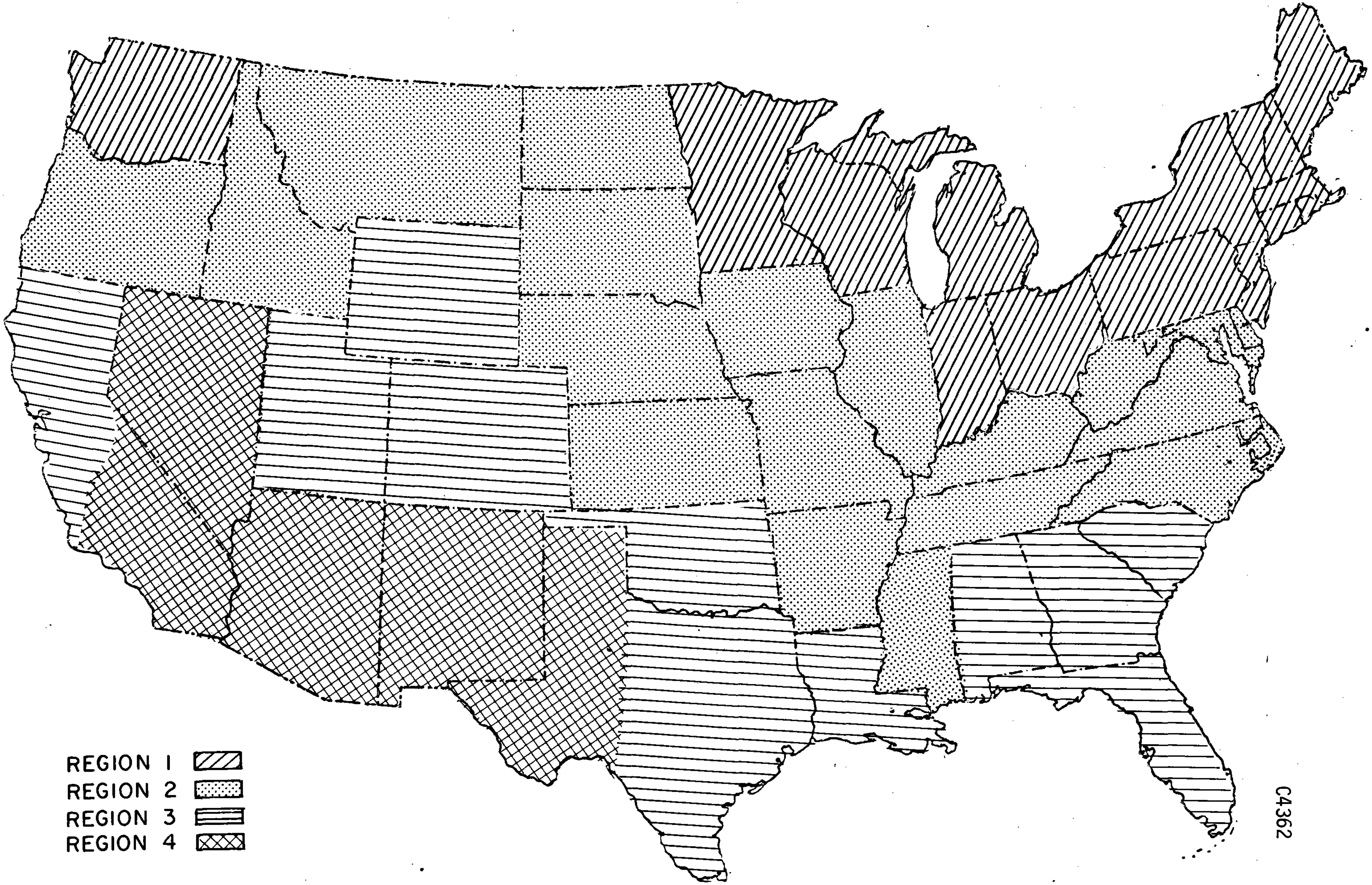

Figure 4-2. Regionalization of the United States According to Solar Radiation

Table 4-1. 1974 Fossil-Fuel Steam-Electric Plant Capacity, Net Generation and Fuel Consumption*

Region and State	Number of Plants Total**	Number of Plants Oil & Gas	Installed Capacity** (MWe)	Net Generation** (10^6 Kwh)	Fuel Consumption Oil (10^3 Barrels)	Fuel Consumption Gas (10^6 ft^3)	Total Energy Consumption (10^9 Btu) Oil	Total Energy Consumption (10^9 Btu) Gas	Total Energy Consumption (10^9 Btu) Total**	Percent of Total Btu Consumed by Type of Fuel Oil	Percent of Total Btu Consumed by Type of Fuel Gas
Region 1											
Connecticut	10	8	3,439	14,850	25,850	-	156,825	-	161,121	97	-
Indiana	31	6	12,432	56,092	2,491	11,146	14,451	11,181	567,095	3	2
Maine	5	5	459	2,187	3,994	-	24,908	-	24,809	100	-
Massachusetts	21	21	5,682	25,122	37,200	5,945	228,871	5,949	257,108	89	2
Michigan	33	15	12,560	57,152	12,679	33,073	75,599	33,793	607,934	12	6
Minnesota	38	29	3,717	16,239	710	32,026	4,472	32,037	183,907	2	18
New Hampshire	5	4	1,093	3,286	1,863	-	11,563	-	36,529	32	-
New Jersey	16	15	6,368	25,221	29,999	10,934	181,182	11,246	267,159	68	4
New York	33	24	16,408	62,390	79,413	27,987	484,411	28,747	670,190	73	4
Ohio	44	9	21,659	96,990	2,641	12,909	16,179	12,470	999,187	2	1
Pennsylvania	37	14	19,468	87,282	17,378	2,428	105,426	2,501	920,554	12	-
Rhode Island	4	4	286	1,195	1,900	1,918	11,667	1,981	15,200	77	13
Vermont	2	2	34	134	1	946	6	946	2,085	-	45
Washington	3	0	1,527	4,214	49	-	282	-	44,923	1	-
Wisconsin	27	9	5,234	21,545	310	22,559	1,874	22,903	236,073	1	9
Total	309	165	110,366	473,899	216,478	161,871	1,317,716	163,754	4,993,874	26	3

Table 4-1. 1974 Fossil-Fuel Steam-Electric Plant Capacity, Net Generation and Fuel Consumption (cont'd)

Region and State	Number of Plants		Installed Capacity**	Net Generation** (10^6 Kwh)	Fuel Consumption		Total Energy Consumption (10^9 Btu)			Percent of Total Btu Consumed by Type of Fuel	
	Total**	Oil & Gas	(MWe)		Oil (10^3 Barrels)	Gas (10^6 ft^3)	Oil	Gas	Total**	Oil	Gas
Region 2											
Arkansas	9	9	2,589	7,528	6,747	39,626	42,621	40,028	82,650	52	48
Delaware	5	4	1,343	6,350	7,362	929	43,929	952	64,991	68	1
District of Columbia	2	2	989	2,301	3,514	-	21,560	-	29,079	74	-
Idaho	-	-	-	-	-	-	-	-	-	-	-
Illinois	36	16	16,500	69,300	6,607	34,080	41,009	35,499	735,421	5	5
Iowa	33	27	3,115	12,861	122	53,364	715	53,740	151,957	1	35
Kansas	34	33	4,642	16,700	1,287	150,747	7,958	150,281	195,524	4	77
Kentucky	20	3	11,227	51,120	208	5,794	1,138	5,924	511,097	-	1
Maryland	10	9	5,089	24,941	25,553	-	157,543	-	255,328	62	-
Mississippi	14	14	4,422	11,080	8,554	37,445	52,045	39,079	124,644	42	31
Missouri	27	15	8,638	35,763	282	45,213	1,689	43,853	383,000	-	12
Montana	4	3	298	1,271	12	551	73	641	14,090	1	4
Nebraska	16	16	1,551	6,478	446	44,053	2,816	43,117	72,606	4	59
North Carolina	14	2	10,241	50,684	4,193	984	25,877	1,010	493,496	5	-
North Dakota	12	1	839	5,742	24	10	138	10	69,310	-	-
Oregon	1	1	111	4	-	217	-	225	225	-	100
South Dakota	7	4	210	676	71	3,388	450	3,386	10,343	4	33
Tennessee	8	1	10,066	45,481	-	9,207	-	9,722	440,704	-	2
Virginia	12	9	5,984	26,128	26,315	1,087	164,126	1,130	270,193	61	-
West Virginia	12	1	12,078	60,953	1,190	33	6,949	36	594,813	1	-
Total	276	170	99,932	435,361	92,487	426,728	570,636	428,633	4,499,471	13	10

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Table 4-1. 1974 Fossil-Fuel Steam-Electric Plant Capacity, Net Generation and Fuel Consumption (cont'd)

Region and State	Number of Plants: Total**	Number of Plants: Oil & Gas	Installed Capacity** (MWe)	Net Generation** (10^6 Kwh)	Fuel Consumption: Oil (10^3 Barrels)	Fuel Consumption: Gas (10^6 ft^3)	Total Energy Consumption (10^9 Btu): Oil	Total Energy Consumption (10^9 Btu): Gas	Total Energy Consumption (10^9 Btu): Total**	Percent of Total Btu Consumed by Type of Fuel: Oil	Percent of Total Btu Consumed by Type of Fuel: Gas
Region 3											
Alabama	13	3	9,663	43,192	1	4,949	5	5,152	439,053	-	1
California (North)	11	11	7,649	20,360	14,048	124,330	86,000	131,930	217,930	39	61
Colorado	18	13	2,605	13,851	524	57,852	3,268	57,598	156,177	2	37
Florida	41	37	15,665	65,347	62,584	145,532	387,154	147,790	681,508	56	22
Georgia	12	8	8,579	32,354	4,562	40,203	27,878	41,359	347,417	8	12
Louisiana	21	21	10,648	37,155	8,751	325,154	53,054	343,445	396,499	13	87
Oklahoma	18	18	5,723	28,986	172	286,511	1,064	298,290	299,366	-	100
South Carolina	14	10	3,825	16,361	5,506	14,346	34,244	14,750	166,218	21	9
Texas (East)	62	64	34,743	126,211	4,679	1,178,455	28,411	1,202,544	1,303,550	2	92
Utah	10	6	992	2,976	120	3,339	709	3,158	33,994	2	9
Wyoming	9	1	2,051	8,684	68	620	394	514	92,965	-	1
Total	229	192	102,143	395,477	101,015	2,181,291	622,181	2,246,530	4,134,677	15	54
Region 4											
Arizona	12	10	2,840	11,672	7,448	29,958	46,006	32,235	118,792	39	27
California (South)	23	23	14,627	50,098	56,796	152,400	348,142	162,077	510,219	68	32
Nevada	6	5	2,583	12,099	681	29,518	4,237	31,617	132,938	3	24
New Mexico	17	13	3,971	19,918	1,054	65,198	6,363	67,442	214,904	3	31
Texas (West)	18	18	2,738	12,587	424	131,795	2,575	134,430	137,005	2	98
Total	76	69	26,759	106,374	66,403	408,869	407,323	427,801	1,113,858	37	38
United States Total	890	596	339,200	1,411,111	476,383	3,178,759	2,917,856	3,266,718	14,741,880	20	22

* Data obtained from *Steam-Electric Plant Factors*, National Coal Association, 1975 edition

** Includes oil, gas and coal fired plants

Table 4-2. Regional Summary of U.S. Fossil-Fuel Steam-Electric Power Plants, 1974

Region	Number of Plants		Installed Capacity* (MWe)	Net Generation (10^6 Kwh)		Fuel Consumption		Total Energy Consumption (10^9 Btu)			Percent of Total Btu Consumed by Type of Fuel		
	Total*	Oil & Gas		Total*	Oil & Gas**	Oil (10^3 Barrels)	Gas (10^6 ft^3)	Oil	Gas	Total*	Oil	Gas	Coal
Region 1	309 (35)***	165 (28)	110,366 (33)	473,899 (34)	138,455 (24)	216,478 (45)	161,871 (5)	1,317,716 (45)	163,754 (5)	4,993,874 (34)	26	3	71
Region 2	276 (31)	170 (29)	99,932 (29)	435,361 (31)	93,390 (16)	92,487 (20)	426,728 (13)	570,636 (20)	428,633 (13)	4,499,471 (31)	13	10	74
Region 3	229 (26)	192 (32)	102,143 (30)	395,477 (28)	268,104 (46)	101,015 (21)	2,181,291 (69)	622,181 (21)	2,246,530 (69)	4,134,677 (28)	15	54	31
Region 4	76 (8)	69 (11)	26,759 (8)	106,374 (8)	78,049 (14)	66,403 (14)	408,869 (13)	407,323 (14)	427,801 (13)	1,113,858 (7)	37	38	25
U. S. Total	890	596	339,200	1,411,111	577,998	476,383	3,178,759	2,917,856	3,266,718	14,741,880	20	22	58

* Includes oil, gas and coal fired plants

** Based on an average plant heat rate of 10,700 Btu/kWh

*** Numbers in parentheses indicate percent of United States total

It shows that, in 1974, the total U. S. net generation of electricity by fossil-fired steam-electric power plants was greater than 1,400 billion kWh. Approximately 42 percent of the energy, or 6.2×10^{15} Btu, required for this generation was supplied by oil and natural gas. The remainder was supplied by coal.

Fuel consumption patterns varied greatly throughout the country. For example, in Region 1 which consists mainly of the northeastern U.S., approximately 475 billion kWh was generated by fossil-fueled steam-electric plants. This was approximately one-third of the total generation by plants of this type. Although almost 70 percent of the electricity generated in this region was by coal-fired plants, the region was still a major user or oil, requiring 45 percent of the total U.S. oil consumption for steam-electric plants. In Region 3, on the other hand, more than 50 percent of the energy for a total net generation of 395 billion kWh was supplied by gas. This consumed almost 70 percent of the nation's amount of gas used for steam-electric plants. The southwestern U.S., Region 4, which has the highest mean daily solar radiation, generated more than 100 billion kWh of electricity by fossil-fueled steam-electric plants. This was about 7 percent of the country's total net generation by this type of plant, of which approximately three-quarters came from oil- and gas-fired plants. Figure 4-3 shows the predominant utility fuel use in different regions of the country.

4.3 SURVEY OF REPRESENTATIVE UTILITIES

In order to obtain a representative sample of plants that could be retrofitted with solar feedwater heaters, a number of electric utilities throughout the United States were contacted. A detailed survey was made of each of their generating units to determine their potential suitability to solar feedwater heating. The following criteria were used.

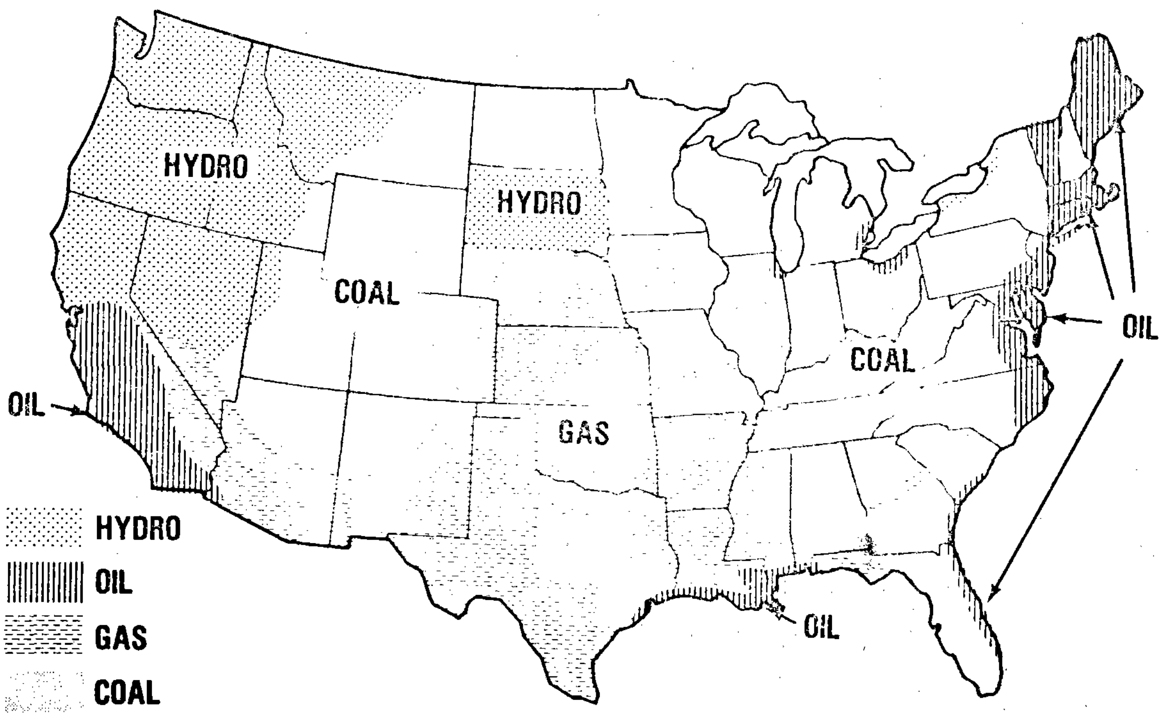

Figure 4-3. Predominant Fuel Use by Electric Utilities, 1973 [Ref. 9]

1. Only oil- or gas-fired steam-electric plants were considered to be potential candidates. Since coal and nuclear fuels are not scarce resources, solar feedwater heating does not appear justified for plants using those fueld. Thus, oil- or gas-fired plants that are scheduled to be converted to coal were also excluded from consideration.

2. Plants scheduled for retirement by the year 1985 or sooner were excluded because the capital investment for solar installations could not be recovered in such a short period of time.

3. The area surrounding the remaining plants was then surveyed in order to ensure that sufficient space was available to install the required solar collector fields. Plants in cities were always eliminated by this criterion; however, it was assumed that open fields or lightly built-up areas adjacent to a power plant could be made available even though that land was not presently owned by the utility.

Information on land availability, planned retirement dates, and the possibility of conversion to coal is not readily available except through interviews with personnel familiar with generating stations on a particular utility company's system. It was not practical to survey every utility in the United States, so a sampling of companies was selected for personal or telephone interviews. A list of these utilities is shown in Table 4-3. The results of the survey of one utility are shown in Table 4-4. For this utility, only a single plant is a potential retrofit candidate. Similar tables were constructed for each of the utilities listed in Table 4-3. A total net generating capacity of over 32,000 MW from oil- and gas-fired generators was covered by the survey. This included 78 stations, which is approximately 13 per cent of the 596 oil- and gas-fired stations in the United States.

Table 4-3. United States Electric Utilities Surveyed

NAME	SERVICE AREA
Atlantic Electric	Southern New Jersey
Arkansas Power & Light	Arkansas
Arkansas-Missouri Power	Arkansas and Missouri
Baltimore Gas and Electric	Baltimore, MD
Delmarva Power and Light	Delaware- Maryland - Virginia Peninsula
Florida Power	Florida
Jersey Central Power and Light	Central New Jersey
Louisiana Power and Light	Louisiana
Mississippi Power and Light	Mississippi
New Orleans Public Service	New Orleans, LA
Philadelphia Electric	Philadelphia, PA
Potomac Electric Power	Washington, DC
Public Service Electric & Gas	Northern and Central New Jersey
Southern California Edison	Southern California

Table 4-5 presents a summary of the results from the nation-wide utility survey. Approximately eight per cent of the capacity will be retired, 37 per cent does not have sufficient space for solar collectors, and 4 per cent cannot be retrofitted because of other reasons. Some soon-to-be retired plants do not have land available, so they were eliminated because of more than one reason. This leaves approximately 51 per cent of the capacity of oil- and gas-fired steam plants potentially available for retrofitting with solar feedwater heating.

Table 4-4. Survey Sample of Oil- and Gas-Fired Steam-Electric Plants

Name of Utility: *XYZ Power Company*

PLANT CAPACITY (MW)

PLANT NAME	RETROFIT NOT POSSIBLE			RETROFIT POSSIBLE
	To Be Retired by 1985	Insufficient Space	Other Reasons*	
Able	134			
Baker		223		
Charlie				201
Dog		406		
Easy		585		
Fox	316			
George		325		
Howie		368		
TOTAL	316	2,041		201

* To be converted to coal, dedicated plant supplying steam to industry and generating by-product electricity

Table 4.5. Summary of Nationwide Survey of Oil- and Gas-Fired Plants

	Generating Capacity (MW)	(% of Total)
Retrofit not possible		
To Be Retired by 1985	2,521	8
Insufficient Space	12,196	37
Other*	1,522	4
TOTAL	16,239	49
Retrofit possible		
TOTAL	16,669	51
Total Net Plant Capacity Included in Survey	32,908	100

* Converting to coal, or dedicated plant supplying steam to industry and generating by-product electricity

4.4 NATION-WIDE IMPACT

The upper bound of the oil and gas fuel resources that could be saved by the use of solar augmented feedwater heating can now be calculated. Single feedwater heaters in modern 200-MW plants have capacities of 60 to 90 million Btu/hr. It is doubtful that more than one FWH in a string could be equipped with solar augmentation, but certainly two is the maximum number that could be so equipped. This limit is established by the temperature range over which solar augmentation is most cost effective (Figure 3-9) and by the inability of the low pressure turbine to accept more steam (Appendix A). The fuel saving efficiency ratio at the optimum augmentation temperature is in the 45 to 50 per cent range (Table 3-1) for the Crane unit which has a heat rate of 9232 Btu/kW. The average heat rate of steam-electric plants in the U.S. is 10,700 Btu/kW [Ref. 8]. The nation-wide average fuel saving efficiency of solar augmentation at the optimum temperature may therefore be taken as

$$0.475 \times \frac{10,700}{9,232} = 0.55.$$

The boiler input to a 200-MW plant with the average U.S. heat rate equals

$$200 \times 10^3 \times 10,700 = 2.14 \times 10^9 \text{ Btu/hr.}$$

If each of two solar augmented feedwater heaters supplies 100×10^6 Btu/hr at a 55% fuel saving efficiency, 110×10^6 Btu/hr of boiler fuel which equals 5.1 percent of total boiler input can be saved.

This maximum amount of solar augmentation is, at best, available during an annual average of six hours per day spread over eight to ten hours. Approximately on-half of electric generation occurs during that period [Ref. 10, Vol. II, Section 2]. Therefore, a maximum of 2.6 per cent of average daily boiler input can be saved in a plant with solar augmentation. On a nation-wide basis, 51 per cent (Table 4-5) of gas- and oil-fired plants are suitable for solar augmentation. All of such plants consumed 6.2×10^{15} Btu during 1974 (Table 4-2). The maximum potential fuel saving through solar feedwater augmentation is therefore equal to

$$0.026 \times 0.51 \times 6.2 \times 10^{15} = 0.82 \times 10^{14} \text{ Btu/yr.}$$

This is more than one per cent of all gas and oil consumed by the nation's utilities, and slightly less than one-quarter per cent of the total national oil and natural gas consumption [Ref. 11]. According to Figure 3-9, the capital investment required to achieve such an annual saving would be $56 billion. In reality, however, that figure pertains to the most favorable location in the U.S. for solar augmentation, and the investment required to equip plants throughout the country with such systems is larger.

An estimate of the reduction in cost-effectiveness for locations other than Inyokern can be made on the basis of insolation received. This was done in Table B-1, Appendix B, where monthly totals of solar radiation incident on collectors at Inyokern, CA and Philadelphia, PA are compared. For fixed collector orientations, Philadelphia receives only 67% of the annual energy received at Inyokern; for rotating collectors, the fraction is even lower. The fraction of energy actually collected is well below these values because of the lower ambient temperatures at Philadelphia compared to Inyokern which reduces collector efficiency. This is apparent from Table 4-6 which shows that the ratio of the energy collected at Philadelphia to the energy collected at Inyokern decreases with increasing collector temperature. Thus, the optimum collection temperature at Philadelphia will be lower than that at Inyokern shown in Figure 3-9.

Table 4-6. Comparison of Annual Energy Collected by a Corning Collector at Different Locations

Average Collector Temperature (°F)	Ratio of Energies Collected at Philadelphia, PA to that at Inyokern, CA (%)
150	58
200	53
250	48
300	41
350	34

The investment required to save a given amount of boiler fuel is, of course, inversely proportional to the amount of energy collected by the solar augmentation system. If Philadelphia is considered typical for Region 1 (see Figure 4-2 and Table 4-1), approximately twice as much investment is required in that region to save one barrel of fuel oil as in Region 4 represented by Inyokern. The equivalent numbers for Regions 2 and 3 are optimistically taken as 1.6 and 1.25, respectively. Using the oil and natural gas consumption figures from Table 4-2, the total investment required to achieve a saving of 0.82×10^{14} Btu/yr is calculated to be $ 30 billion, a staggering sum equal to total electric utility investment for one to two years [Ref. 21].

A thorough economic analysis of the implications of these results is beyond the scope of this study. However, it is clear that neither the nation nor the utilities can affort an investment of that size in return for one-quarter of one per cent reduction in the country's consumption of oil and natural gas.

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APPENDIX A

SOLAR AUGMENTED FEEDWATER HEATING

A major consideration in the analysis of the desirability of solar augmented feedwater heating is the determination of the energy displacement from fossil fuel to solar. The question to be answered is: "How many Btu of fossil fuel energy are saved by the addition to the boiler feedwater of one Btu of energy from a solar augmentation system?" Two methods for answering this question were used. One is approximate and is based on considerations of steam enthalpy. The other one is considered to be "accurate"; it uses a generalized heat rate computer program employed by the Baltimore Gas and Electric Company and the Philadelphia Electric Company for plant cycle analysis.

The fuel saving efficiency of solar augmentation, E, is defined as ratio of the reduction in energy required by the boiler, Q_R, to the amount of solar energy collected, Q_S.

$$E \equiv \frac{Q_R}{Q_S} \times 100 \ . \qquad \text{(A-1)}$$

The value of E may be derived in terms of the plant parameters shown in the simplified cycle diagram in Figure A-1. It is assumed that solar energy input before FWH No. 2 results in a reduction in the extraction steam flow to FWH No. 2, extraction flows to other FWH's are unaffected, and all the enthalpy values, h, remain unchanged compared to the case without solar augmentation. An energy balance leads to an equation for the solar energy input, Q_s, in terms of the reduced extraction flow, ΔW, the extraction steam enthalpy, h_e, and the enthalpy of water leaving the condenser, h_c.

$$Q_s = \Delta W \ (h_e - h_c) \qquad \text{(A-2)}$$

The additional plant output, ΔL, resulting from increased steam flow through the turbine is related to the useful work done by the steam as follows:

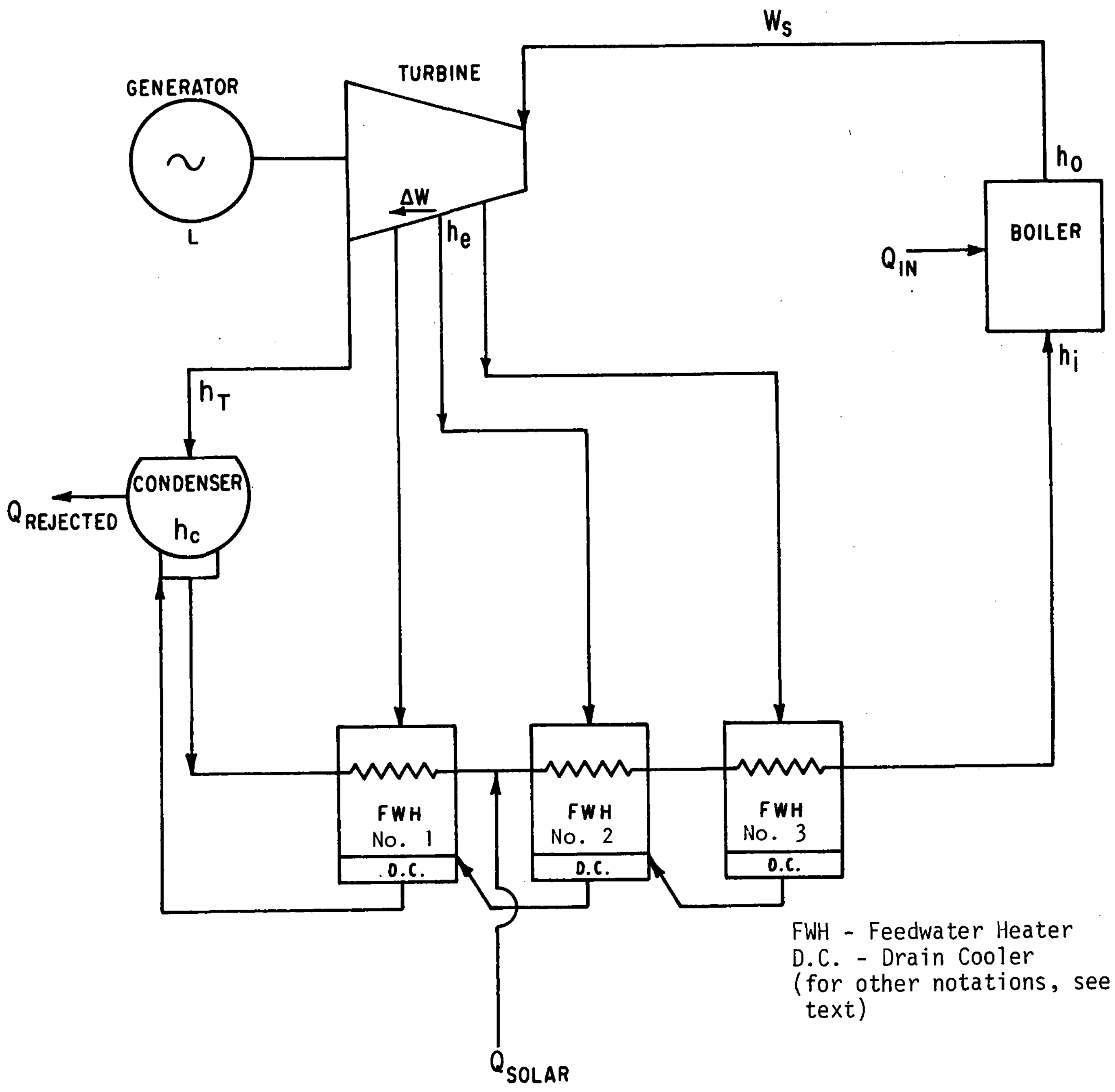

Figure A-1. Simplified Cycle Diagram for Solar Augmented Feedwater Heating

$$\Delta L = \Delta W \ (h_e - h_T)\eta_g , \tag{A-3}$$

where h_T is the enthalpy of the steam leaving the low pressure turbine, and η_g is the generator efficiency.

In order to compare a base case without solar augmentation to a case with solar input, it is assumed that the plant load in both instances is the same. Therefore, in order to maintain the plant output at a specified load, L, the main steam flow for the case with solar augmentation would have to be throttled back an amount ΔW_s such that

$$\Delta W_s = \left(\frac{\Delta L}{L}\right) W_s , \tag{A-4}$$

where W_s is the main steam flow for the base case. The reduced heat input to the boiler, Q_R, becomes

$$Q_R = \left(\frac{\Delta L}{L} \ W_s\right) \frac{(h_o - h_i)}{3413 \ \eta_B \eta_g} \tag{A-5}$$

where $(h_o - h_i)$ is the enthalpy rise of the working fluid across the boiler, η_B is the boiler efficiency and 3413 is the conversion factor from kWh to Btu. Substituting Eqs. (A-2), (A-3) and (A-5) into Eq. (A-1) yields an expression for the fuel saving efficiency,

$$E = \left(\frac{h_e - h_T}{h_e - h_c}\right) \frac{1}{3,413} \left[\frac{W_s \ (h_o - h_i)}{\eta_B \ L}\right] \times 100 \tag{A-6}$$

The third term on the right-hand side of Eq. (A-6) is, by definition, the plant heat rate, HR, so that E may finally be written as

$$E = \left(\frac{h_e - h_T}{h_e - h_c}\right) \frac{HR \times 100}{3,413} \ . \tag{A-7}$$

The fuel saving efficiency increases as the value of the replaced extraction steam enthalpy increases. This is to be expected because, as steam expands, in the turbine, it performs work. By the time the steam expands to the extraction point for the lowest pressure feedwater heater, most of its usable energy has been converted into mechanical energy. The value of steam at the low pressure end, therefore, is minimal. It should also be noted that the fuel saving efficiency of solar augmentation increases as plant efficiency decreases. In general, solar augmentation is most effective in conserving energy at high temperature FWH's and at plants with high heat rates.

A numerical example has been worked out taking values for h_c, h_T and h_e from the base case shown in Figure A-2 and η_B equal to 0.85. The fuel saving efficiency has been calculated for various solar heat input locations and three plant heat rates, 9,000, 10,700, and 13,000 Btu/kWh. (The average plant heat rate for oil and gas-fired steam plants in the U.S. is 10,700 Btu/kWh [8].) Results presented in Table A-1 and Figure A-3 show that, depending on the plant and the location of the solar energy input, 100 Btu of solar energy can reduce the fuel requirement for the boiler by approximately 20 to 90 Btu. This compares to the net useful solar capacity of 68% for solar feedwater heating as given by Zoschak and Wu [12].

Table A-1. Fuel Saving Efficiency of Solar Augmentation at Various Feedwater Heaters

Solar Heat Input Location	Extraction Steam Enthalpy, h_e (Btu/lb)	$\left(\frac{h_e-h_T}{h_e-h_c}\right)$*	Fuel Saving Efficiency (%) Plant Heat Rate (Btu/kWh) 9000	10,700	13,000
Before FWH No. 1	1113	.084	22	26	32
" " " 2	1224	.171	45	54	65
" " " 3	1259	.195	52	61	74
" " " 4	1258	.194	51	61	74
" " " 5	1323	.236	62	74	90
" " " 6	1339	.246	65	77	93

*h_T = enthalpy at exhaust of low pressure turbine = 1025 Btu/lb

h_c = enthalpy of water leaving condenser = 60 Btu/lb

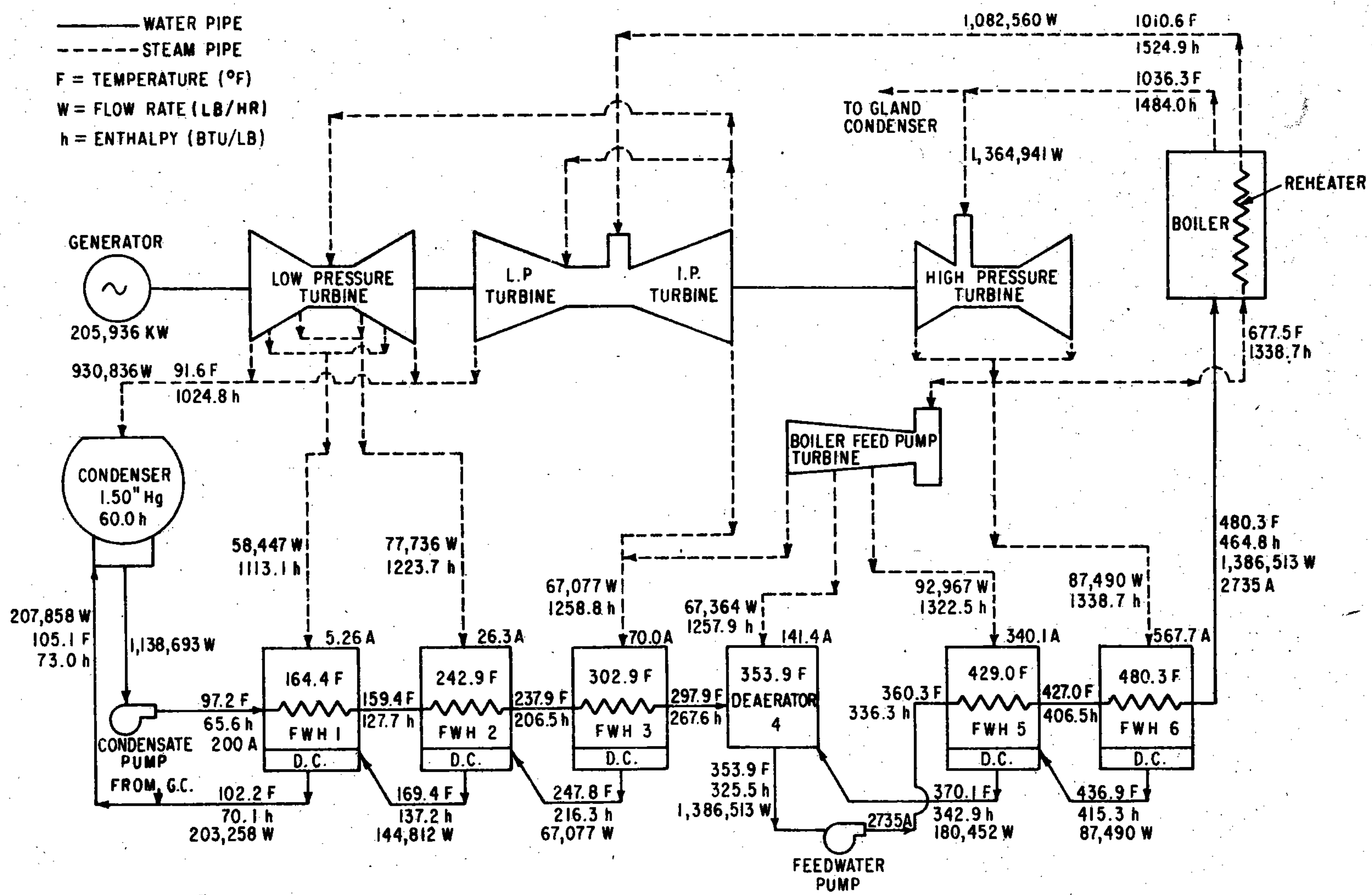

Figure A-2. Base Case Heat Balance (No Solar Input)

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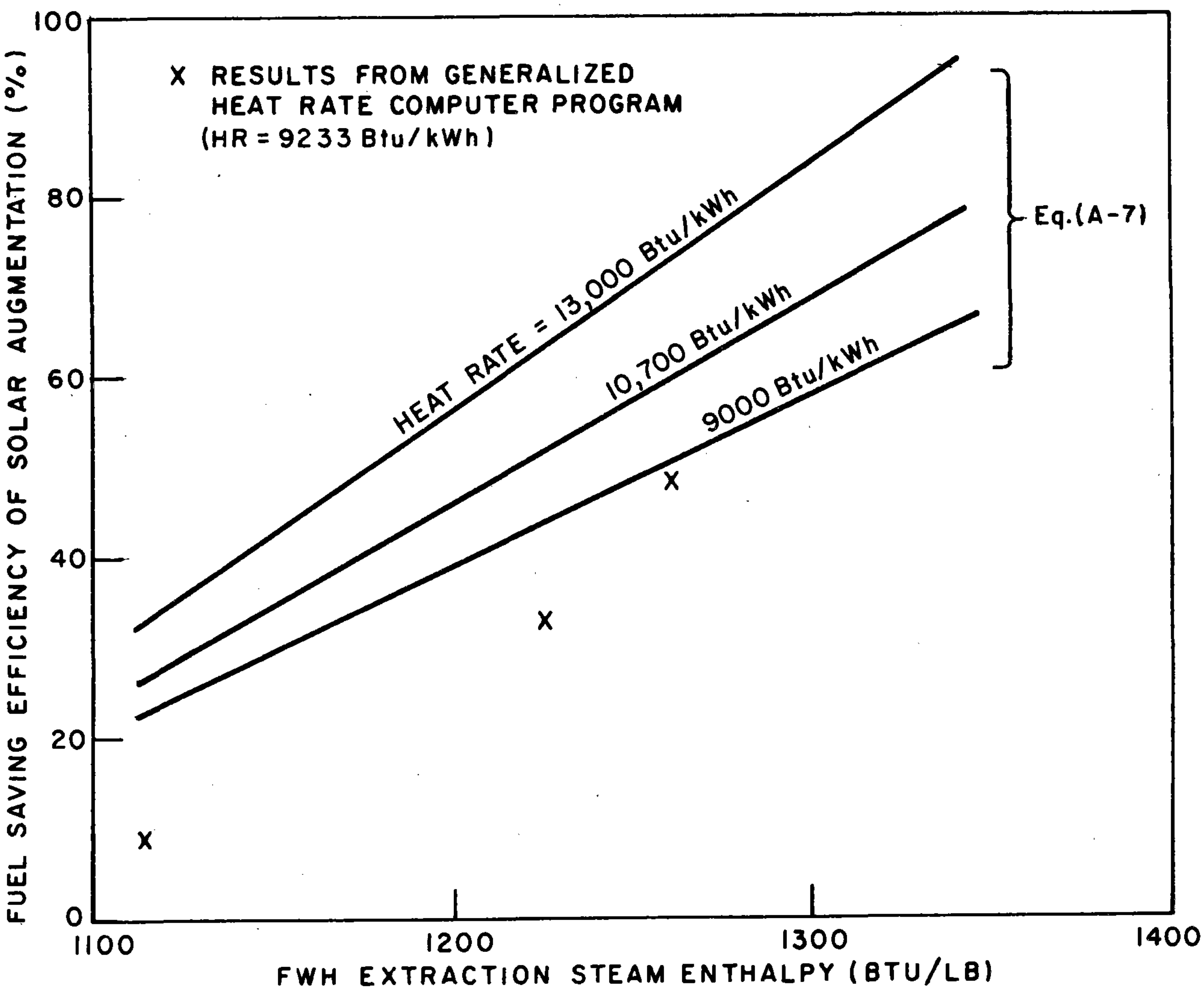

Figure A-3. Calculated Fuel Saving Efficiencies

The results obtained from Eq. (A-7) were compared with those obtained from a generalized heat rate program [13,14]. This digital computer program has been developed over several years by Philadelphia Electric Company and Baltimore Gas and Electric Company personnel, and it is used by these utilities for new plant contract cycle heat balance analyses. The program is very general in nature and can be set up to handle a wide variety of power plant cycles. The particular cycle selected for the solar feedwater heating analysis was Baltimore Gas and Electric Company's Crane Unit No. 2. This unit is a base load 200 MWe oil-fired plant. When it went commercial in February, 1963, the plant was coal-fired, but it was converted to oil in 1970. The FWH string has three low-pressure and two high-pressure closed feedwater heaters and one open heater (deaerator). The cycle conditions for the base case without solar augmentation are shown in Figure A-2. A steam-driven boiler feedpump turbine supplies extraction steam to several of the feedwater heaters which complicates the cycle slightly.

The heat rate program was modified slightly to allow an additional heat input ahead of any feedwater heater. This simulates the solar augmented FWH scheme shown in Figure 3-3. The solar heat input was varied by specifying the enthalpy rise of the feedwater between FWH's. The throttle steam flow, the boiler exit temperature and pressure, and the condenser pressure were fixed for each run. The program was rerun for various solar input locations and energy levels, and new energy and heat flow balances were calculated each time. Figure A-4 presents an example of a section of the computer output with data on three FWH's for the case with a solar input of 45.5 million Btu per hour (enthalpy rise of 40 Btu/lb of feedwater flow) between FWH nos. 1 and 2. The entire output consists of pressures, temperatures, enthalpies, and flow rates for more than 120 points in the system. The cycle diagram for this case is shown in Figure A-5. Comparing this figure to the base case, Figure A-2 shows that, as expected, the predominant effect of solar

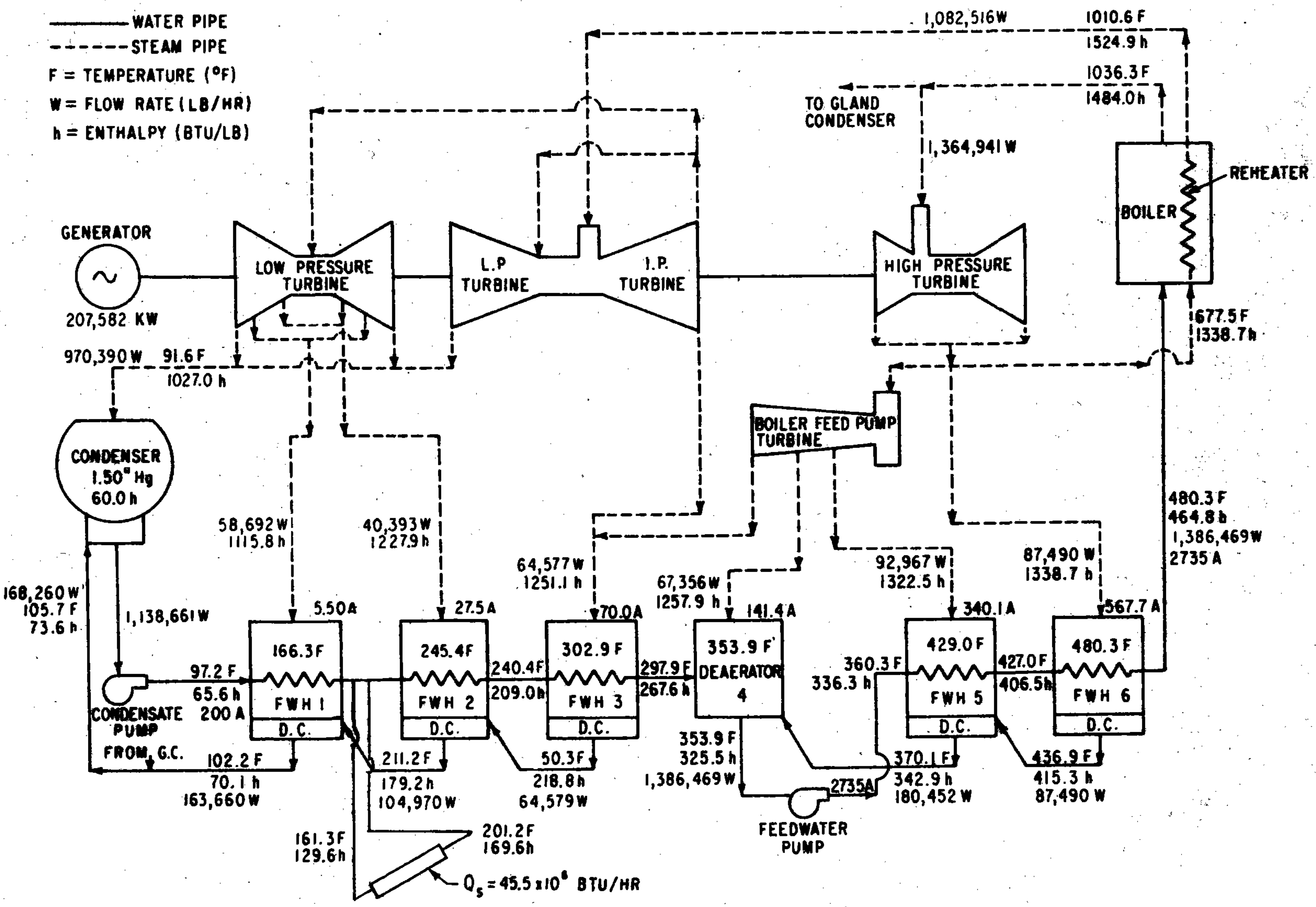

Figure A-4. Heat Balance With 45.5 Million Btu/hr Solar Energy Input Before FWH No. 2

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FEEDWATER HEATERS

		PRESSURE (PSIA)	TEMPERATURE (F)	ENTHALPY (BTU/LB)	FLOW RATE (LB/HR)
NO.21 FEEDWATER HEATER					
EXTRACTION TO HEATER		5.50	170.85	1115.78	58692.
FEEDWATER TO HEATER		200.00	97.20	65.63	1138661.
FEEDWATER FROM HEATER		200.00	161.30	129.59	-1138661.
DRAINS FROM HEATER		5.50	102.19	70.09	-163660.
DRAINS TO HEATER		27.50	211.20	179.22	104970.
TERMINAL TEMPERATURE DIFFERENCE	5.0 F				
DRAIN COOLER APPROACH	5.0 F				
SOLAR HEAT COLLECTOR					
UPSTREAM PROPERTIES		200.00	201.23	169.59	-1138661.
DOWNSTREAM PROPERTIES		200.00	161.30	129.59	1138661.
INCREMENTS		0.0	0.0	0.0	
HEAT LOSS FROM SYSTEM	0.0 M BTU				
NO.22 FEEDWATER HEATER					
EXTRACTION TO HEATER		27.50	379.72	1227.92	40393.
FEEDWATER TO HEATER		200.00	201.23	169.59	1138661.
FEEDWATER FROM HEATER		200.00	240.40	209.03	-1138661.
DRAINS FROM HEATER		27.50	211.20	179.22	-104970.
DRAINS TO HEATER		59.98	250.32	218.80	64579.
TERMINAL TEMPERATURE DIFFERENCE	5.0 F				
DRAIN COOLER APPROACH	10.0 F				
NO.23 FEEDWATER HEATER					
EXTRACTION TO HEATER		59.98	437.71	1251.13	64577.
FEEDWATER TO HEATER		200.00	240.40	209.03	1138661.
FEEDWATER FROM HEATER		200.00	297.91	267.58	-1138661.
DRAINS FROM HEATER		59.98	250.32	218.80	-64579.
TERMINAL TEMPERATURE DIFFERENCE	5.0 F				
DRAIN COOLER APPROACH	10.0 F				

Figure A-5. Example of Output From Generalized Heat Rate Program With Solar Energy Input of 45.5 Million Btu/hr Before FWH No. 2

augmentation is felt on the extraction flow to the upstream FWH. The extraction flow to FWH no. 2 dropped from 77,736 lb/hr in the base case to 40,393 lb/hr with a 45 million Btu/hr solar input. In comparison, changes in the adjacent FWH's were relatively minor.

A summary of the results of the generalized heat rate program is presented in Table A-2. The amount, as well as the location of the solar heat input was varied for four different runs. In order to make comparisons with the base case, the main steam flow was throttled to keep the net plant output constant. This resulted in a reduction in heat input to the boiler. The ratio of fuel savings to gross solar heat input gives a value for the fuel saving efficiency. This is compared to the value calculated by Eq. (A-7). For runs 1 and 2 (solar input before FWH no. 1) Eq. (A-7) predicts a 23% fuel saving efficiency, while the heat rate program predicts 8%. The corresponding values for run 4 (solar input before FWH no. 3) are 53% and 49%, respectively. The fuel saving effectiveness of solar augmentation as a function of extraction steam enthalpy is presented in Figure A-3 for both methods of determination.

The reason for the different results, particularly at the low pressure FWH, are as follows. Eq. (A-7) was derived assuming constant values for pressure, enthalpy, and temperature at the various extraction points. By comparing Figures A-2 and A-4 one sees that these values change slightly. In particular, small changes in enthalpy at steam extraction points can result in comparatively large incremental changes in plant output. This occurs because a small change in the energy of steam multiplied by a large steam flow can significantly change the turbine output and therefore the energy conservation potential of solar energy. This effect is more dominant at the lower pressure FWH's, and indeed Table A-2 reflects the fact that the approximate and the generalized heat rate calculations for the fuel savings efficiency of solar augmentation agree more closely for higher pressure FWH's. From this comparison it can be concluded that a detailed heat balance analysis is required in order to accurately determine the effect of solar augmentation at the low pressure feedwater heaters. At the higher pressure FWH's, the approximate analysis gives satisfactory results.

Table A-2. Fuel Savings Calculated from Generalized Heat Rate Program

Run No.	Solar Heat Input Location	FWH Temperature (°F)	Extraction Steam Enthalpy (Btu/lb)	Solar Heat Input Q_s (10^6 Btu/Hr)	Boiler Heat Input Q_{in} (10^6 Btu/Hr)	Net Plant Output (kW)	Fuel Savings $\frac{\Delta Q_{in}}{\eta_B}$* ($10^6$ Btu/Hr)	$\frac{\text{Fuel Saving}}{\text{Solar Heat Input}}$ (%) $\frac{\Delta Q_{in}}{Q_s \eta_B}$	Calculated From Eq. (A-7)
Base Case	—	—	—	0	1614.71	205,937	—	—	—
1	Before FWH #1	164	1113	22.8	1613.17	↓	1.82	8	23
2	↓	↓	↓	45.5	1611.65	↓	3.60	8	23
3	Before FWH #2	243	1224	45.5	1602.18	↓	14.7	32	44
4	Before FWH #3	303	1259	22.8	1605.24	↓	11.1	49	53

*Assumes boiler efficiency, η_B, equal to 0.85.

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APPENDIX B

B-1. SUITABLE SOLAR COLLECTORS

In a steam-electric plant, the condensate leaving the condenser at a temperature of approximately 100°F passes through a series of feedwater heaters before being returned to the boiler at a temperature of approximately 550°F. Therefore, solar collectors used for power plant feedwater heating must supply thermal energy at temperatures somewhere in the range of 100°F to 550°F.

B-1.1 Flat Plate Collectors

The most common type of collector presently available is the flat plate collector shown schematically in Figure B-1. One or more transparent covers (windows) allow solar radiation to reach the absorber but inhibit convection and radiation heat loss to the environment. The upper surface of the absorber is coated with a black, energy absorbing surface. The insulation reduces heat loss by conduction from the back of the absorber.

Absorber coatings can be either flat black or selective black. A flat black coating has an absorptivity (and emissivity) which is relatively independent of wavelength. A selective black surface, however, is an excellent absorber of solar radiation in the visible range, but is a poor emitter at collector operating temperatures in the infrared range of the spectrum. Therefore, an absorber with a selective black coating has a lower radiation heat loss than one with a flat black coating.

A flat plate collector is best suited to operating temperatures less than 150°F above the ambient temperature. For applications requiring higher temperatures, it is necessary either to concentrate the solar radiation onto the absorbing surface or to evacuate the space between the absorber and the transparent cover. The vacuum eliminates convective heat loss and greatly reduces conductive heat loss.

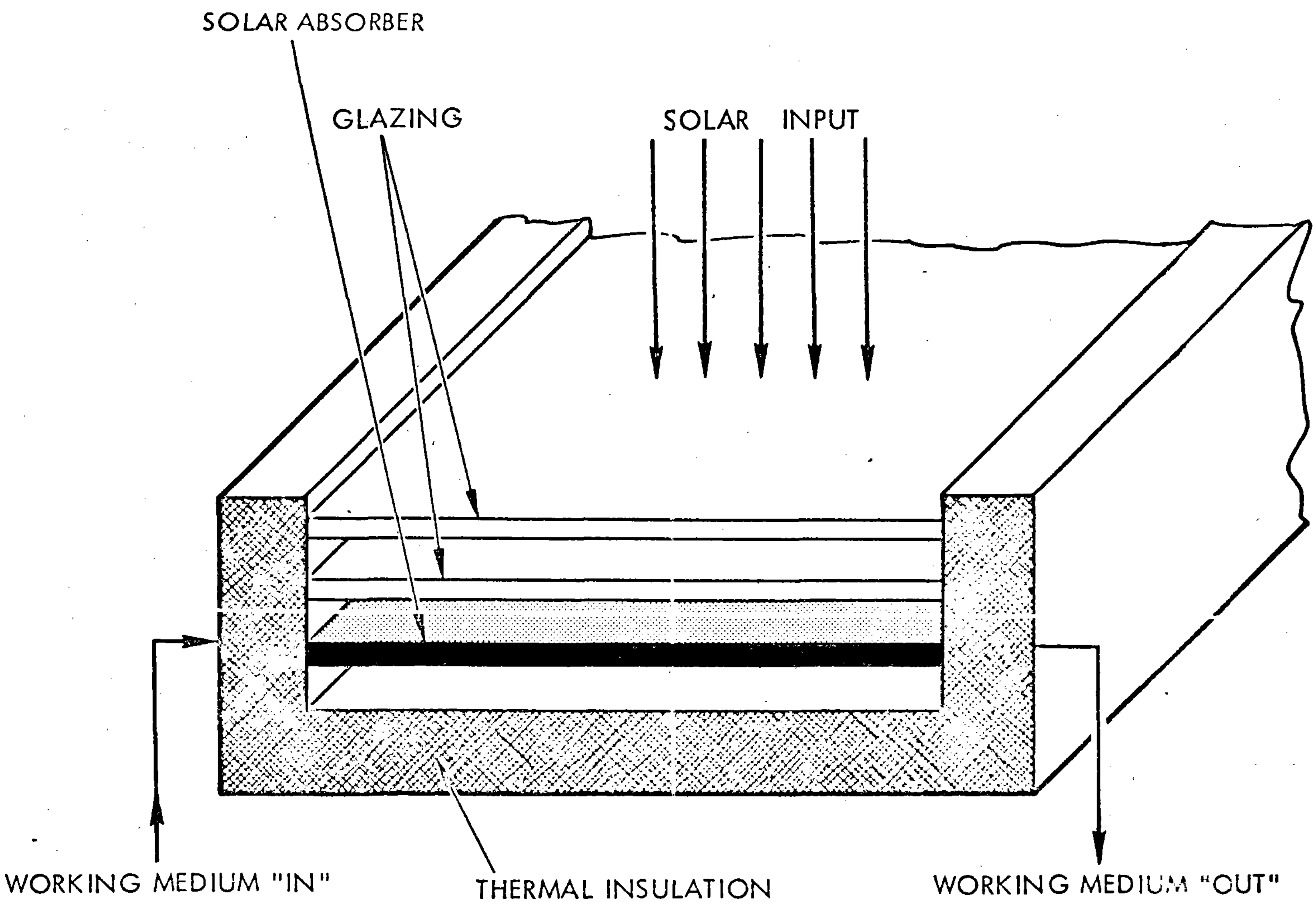

Figure B-1. Flat Plate Solar Collector

Two companies, Corning Glass Works and Owens-Illinois, Inc., have developed non-concentrating collectors which achieve higher operating temperatures through the use of a vacuum. These collectors are quite similar in basic construction (see Figure B-2). They consist of selective black absorbers inside evacuated glass tubes. The absorber of the Corning unit is a metal plate inside a single glass tube, whereas the absorber of the Owens-Illinois collector is a black coated glass tube concentric with the outer envelope consisting of two concentric glass tubes; the space between the last two tubes is evacuated. The Corning collector can operate at temperatures in the 350°F to 400°F range with a reasonable efficiency. The Owens-Illinois collector is designed to operate at temperatures of 300°F or less.

B-1.2 Concentrating Collectors

By concentrating solar energy on an absorbing surface through mirrors or lenses, concentrating collectors can operate at temperatures of more than 1000°F. To a large extent, the operating temperature is a function of the concentration ratio which is defined as the ratio of the collector aperture area to the absorber area. As the concentration ratio increases, the operating temperature increases. A disadvantage of concentrating collectors is that, for concentration ratios greater than about three, the collector cannot utilize the diffuse component (radiation scattered and reflected by the earth's atmosphere) of the incident solar energy. On cloudy days, the incident radiation may be predominately diffuse.

Numerous concentrator designs have been proposed, and a few are now commercially available. One type is a parabolic trough collector. Sunlight reflected from a parabolic trough-shaped mirror is focused on a black tube. The black absorbing tube can be a pipe through which the working fluid flows, or it can be a heat pipe which transfers the absorbed energy to an external energy transfer loop. Roland Winston at the University of Chicago has invented a non-imaging concentrating collector. Because it is non-imaging, it can also utilize some of the diffuse energy incident on the collector. The collector consists of numerous parallel troughs which have parabolic reflecting walls. The absorber is located at the bottom of the trough (Figure B-3).

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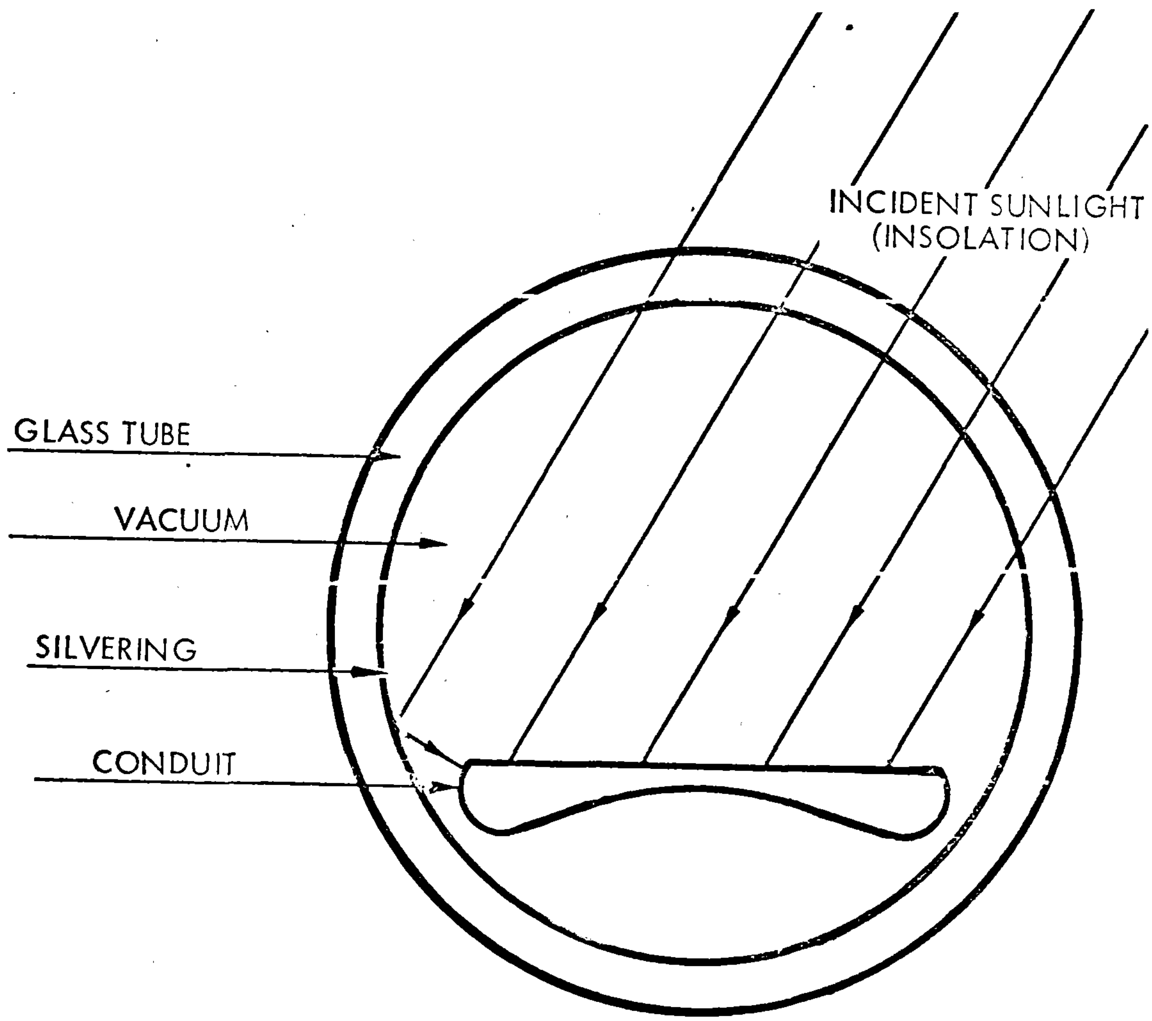

Figure B-2. Evacuated Tube Solar Collector

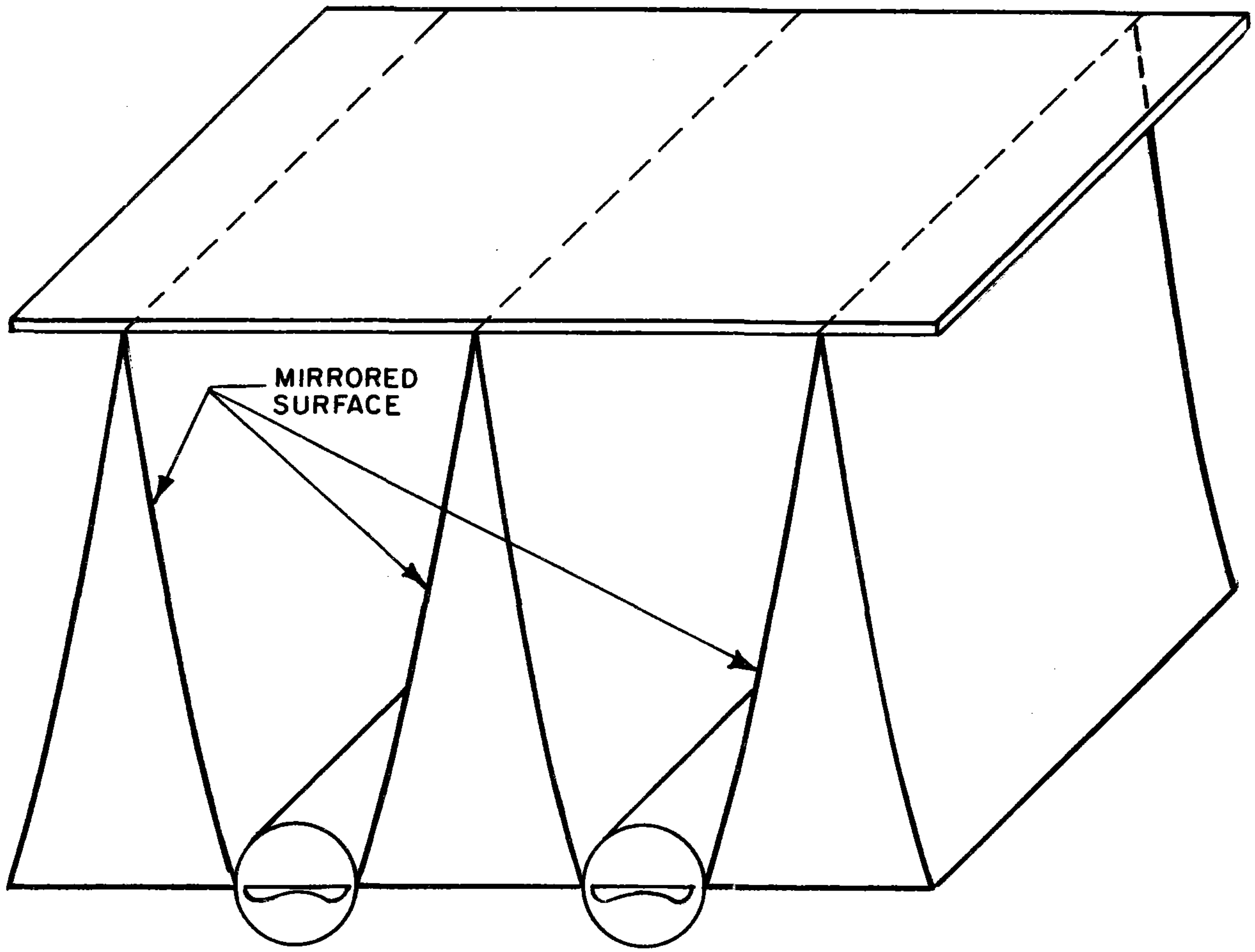

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Figure B-3. Compound Parabolic Concentrator (Winston Collector)

This collector is generally denoted as the Compound Parabolic Concentrator.

Although most solar concentrators use mirrors, Northrup has developed a concentrator which uses a cylindrical Fresnel lens made of extruded acrylic. The collector has the shape of a long trough with the lens located at the top and the absorber at the bottom of the trough. At present, this device has been optimized for use with solar space heating and cooling systems, but its design concept is inherently applicable to higher operating temperatures as well (Figure B-4).

Since solar feedwater heating is desired as a short-term technology to be applied within the 1976-1985 decade, only collectors which are presently available or which are under active development were considered. Based on the required operating temperatures, four different collector types were chosen and their performance was analyzed as being representative of collectors satisfying the above requirements.

The first collector is a flat plate collector manufactured by the Chamberlain Manufacturing Corporation. This collector has two cover plates of low iron glass and a selective black absorber coating with an absorptivity of 0.94 and an emissivity of 0.12. The second collector is the Northrup collector described above which uses a Fresnel lens to concentrate sunlight. The third collector is the Corning Glass evacuated tube collector, and the fourth collector is the compound parabolic concentrator (CPC) originated by Winston; the CPC collector used in this study concentrates sunlight on a tubular evacuated absorber.

These particular collector types were chosen because they perform somewhat better than typical flat plate collectors and because they do not require sophisticated expensive two-axis continuous tracking mechanisms (see Section B-2). The instantaneous efficiency curves used to model the performance of each collector are as follows:

(a) Chamberlain collector

$$Q = \left(-0.75 \times \frac{[T_{inlet} - T_{ambient}]}{I_{total}} + 0.773\right) \times I_{total}$$

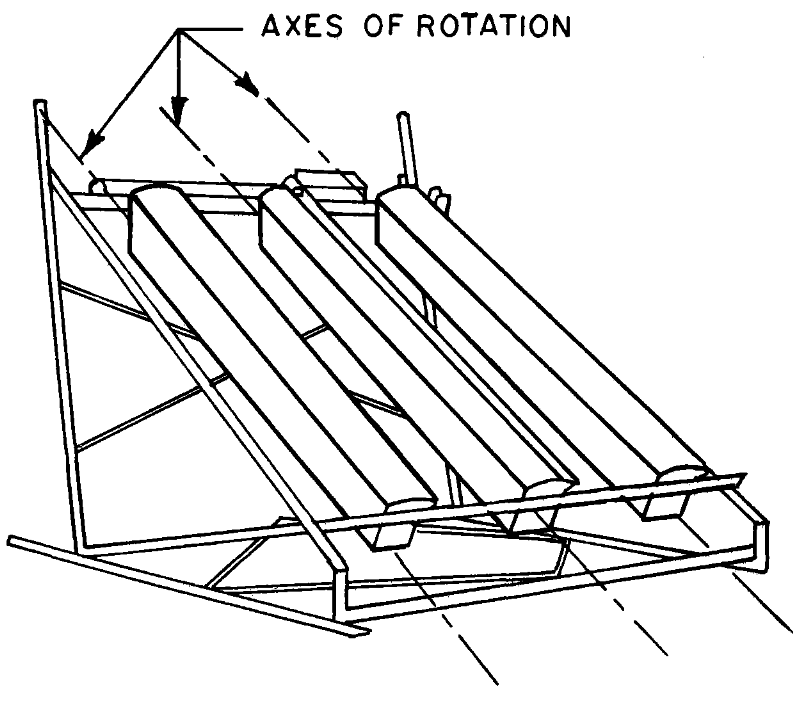

Figure B-4. Northrup Collector

(b) Northrup Collector

$$Q = \left(-0.685 \times \frac{[T_{inlet} - T_{ambient}]}{I_{total}} + 0.881\right) \times I_{direct}$$

(c) Corning Collector

$$Q = \left(0.87 - \frac{2.42 \times 10^{-10}(T_{plate} + 460)^4}{I_{total}}\right) \times I_{total}$$

(d) CPC Collector

$$Q - \left(0.65 - \frac{1.297 \times 10^{-10}(T_{plate} + 460)^4}{I_{total}}\right) \times I_{direct}$$

where

Q	=	rate of energy collection ($Btu/hr\text{-}ft^2$)
T_{inlet}	=	collector inlet temperature (°F)
$T_{ambient}$	=	ambient air temperature (°F)
T_{plate}	=	average collector plate temperature (°F)
I_{total}	=	total solar radiation (direct + diffuse) incident on the collector ($Btu/hr\text{-}ft^2$)
I_{direct}	=	direct component of the solar radiation incident on the solar collector ($Btu/hr\text{-}ft^2$)

The above equations were developed based on performance curves in manufacturers' literature and from information obtained by contacting the manufacturer and/or developer of the particular collectors. For additional information on the four representative collectors chosen, see References [17] through [20].

B-2. METHODS OF COLLECTOR ORIENTATION

The concentrators described so far consist of individual units having both a mirrored reflecting surface and an absorber. Several research teams are currently investigating the feasibility of using a large field of movable mirrors (heliostats) to concentrate sunlight on a single absorber located at the top of a tower situated in the center or along one edge of the mirror field [Ref. 7]. This concept was not considered in the present study. The consideration of solar collector orientation devices was limited to those employing at most a single-axis tracking mechanism.

The simplest and least expensive method of orienting a solar collector is to have it remain stationary. In the northern hemisphere, a fixed position collector is usually oriented south and is tilted from the horizontal by a certain tilt angle. The tilt angle is chosen to maximize energy collection over a given period of time. A high tilt angle (greater than the latitude) maximizes energy collection during the winter, and a low tilt angle maximizes it during the summer. A tilt angle approximately equal to the latitude maximizes the annual energy collection.

The exact value of the tilt angle is not critical, and a variation of a few degrees from the optimum will have a minimal effect on the solar system performance. It is also possible that, for a given solar system, the tilt angle which maximizes the incident solar radiation and the tilt angle which maximizes the amount of usable energy collected may differ by a few degrees.

A solar collector which tracks or follows the movement of the sun receives significantly more solar radiation than a stationary collector. This is illustrated in Figure B-5, in which there are two sets of curves giving clear day incident radiation on June 21, and on December 21, respectively. Within each set, there is one curve showing total radiation incident on a fixed, south-facing solar collector and one curve showing radiation incident on a tracking collector. It can be seen that a tracking collector receives 30% more radiation on a clear day on June 21 than a fixed collector, and 20% more on December 21. It is also evident from Figure B-5 that a solar collector can capture more solar energy during the summer than during the winter.

Tracking mechanisms can be continuous or periodic. Periodic tracking involves the adjustment of the collector position on a weekly, monthly, or seasonal basis. Continuous mechanisms use one or two axes of movement. Tracking systems with one axis of movement normally follow the east-to-west (E-W) movement of the sun, while the collector tilt angle remains fixed. Two-axis systems include both an E-W movement and an adjustable tilt angle.

B-3. ENERGY COLLECTION

B-3.1 Methodology for Determining Solar Radiation Incident on a Collector

The availability of solar radiation at particular locations can be determined by using a procedure developed by Liu and Jordan [Ref.15]. Monthly values of average daily total solar radiation on a horizontal surface for Inyokern, California were calculated based on measured data for the years 1962 and 1963 [Ref.5]. These values are representative of the highest insolation rates available in the United States. Figure 1.1 of Reference [15] contains curves which relate hourly radiation to daily total radiation on a horizontal surface. These curves were used to develop daily profiles of radiation on a horizontal surface for each month. The profiles have the form

$$H = A \times \ln (B) - C$$

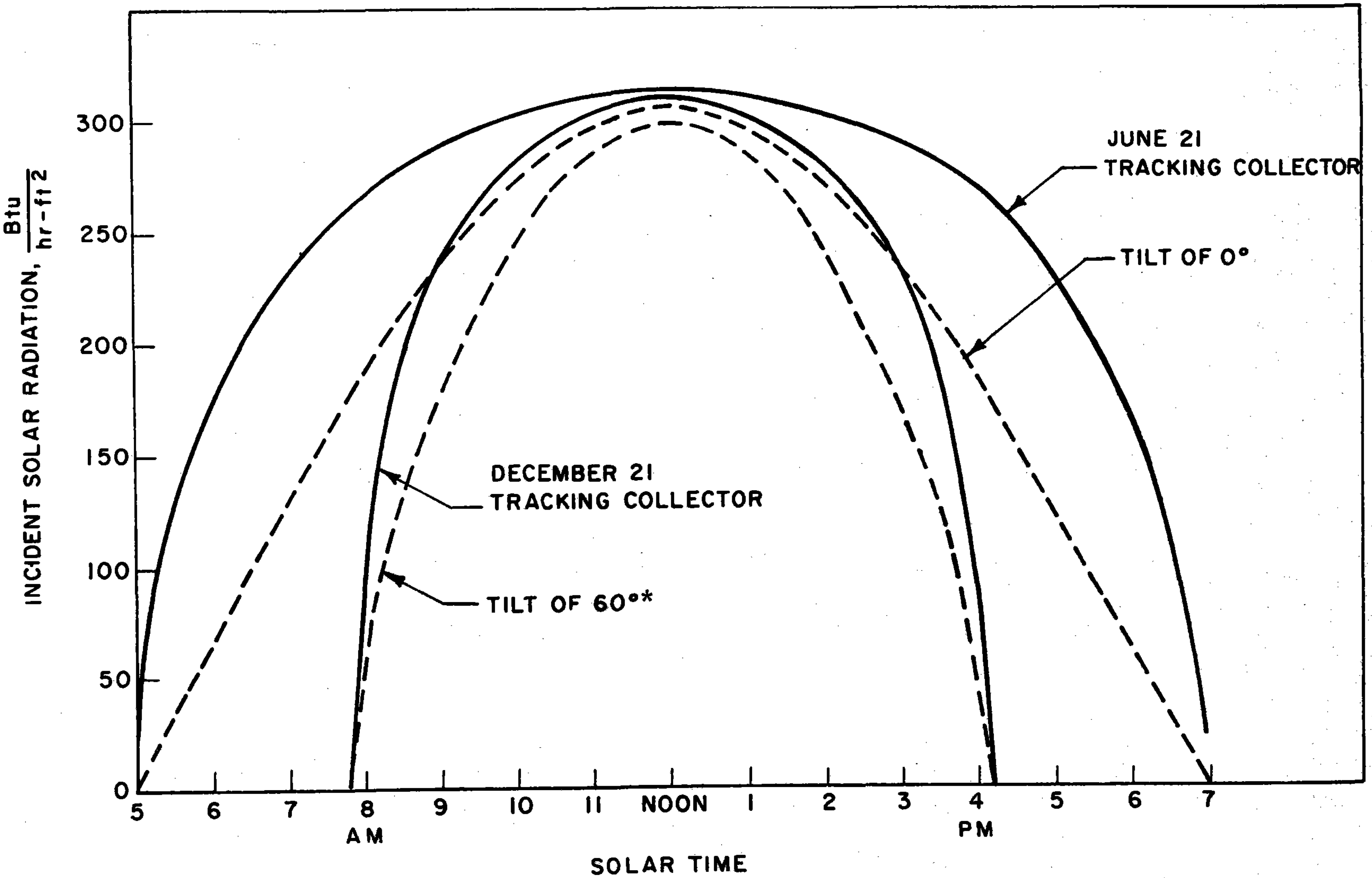

Figure B-5. Clear Day Solar Radiation Incident on Fixed and Tracking Collectors for Dec. 21 and June 21 (40° N. Latitude)

*Above horizontal plane.

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where H is the hourly radiation on a horizontal surface (Btu/hr.ft^2) calculated at the midpoint of the hour, A and C are constants for a given month and B varies throughout the day. The values for A, B, and C are shown in the tables below.

Month	A	C
Jan.	423.0	856.3
Feb.	422.9	827.9
Mar.	503.8	964.6
Apr.	492.9	896.9
May	477.3	847.9
June	482.8	847.0
July	498.6	882.4
Aug.	484.6	872.0
Sept.	504.2	954.7
Oct.	433.9	842.7
Nov.	434.7	877.0
Dec.	418.6	854.6

Time of Day		B
AM	PM	
5:30	6:30	6
6:30	5:30	7
7:30	4:30	8
8:30	3:30	9
9:30	2:30	10
10:30	1:30	11
11:30	12:30	12

Solar collectors are generally mounted at a tilt with respect to the horizontal to increase the amount of solar radiation received. The radiation incident on the tilted collector surface is calculated by a procedure based on the work of Liu and Jordan [Ref.16]. The direct and diffuse components of radiation (I_{DIR} and I_{DIFF}) on a horizontal surface are given by

$$I_{DIFF} = H\,[1.0045 + 2.6313\,K_t^3 - 3.5227\,K_t^2 + 0.04349\,K_t]$$

$$I_{DIR} = H - I_{DIFF}$$

where $K_t = H/H_0$;

H = hourly total radiation on a horizontal surface,

H_0 = extraterrestrial radiation flux per unit area on a horizontal surface;

$H_0 = [1 + 0.33 \cos (360\ N/365)]\ S_c \cos \theta$;

N = day of year ;

S_c = solar constant ;

θ = angle of incidence of solar rays on a horizontal surface (i.e., angle between the incident ray and the normal to the surface).

The total radiation incident on a tilted collector surface (H_T) is given by

$$H_T = I_{DIR} \times \frac{\cos \theta_T}{\cos \theta} + I_{DIF} \times (1/2)(1 + \cos \Sigma) + (H\times r)\ (1/2)(1-\cos \Sigma)$$

where

θ_T = angle of incidence of solar rays on an inclined collector surface;

Σ = collector tilt angle (Figure 6);

r = ground reflectivity (r=0.2).

The incidence angles for a horizontal surface (θ) and for a stationary south-facing solar collector (θ_T) are given by:

$$\cos(\theta) = \cos(LAT)\ \cos(DEK)\ \cos(HRNO) + \sin(LAT)\ \sin(DEK)$$

$$\cos(\theta_T) = \sin(\theta)\ \cos(\phi)\ \sin(\Sigma) + \cos(\theta)\ \cos(\Sigma)$$

where

DEK = solar declination = $23.45 \sin\ (284 + N) \frac{360}{365}$;

N = day of year;

HRNO = number of minutes from solar noon x 0.25;

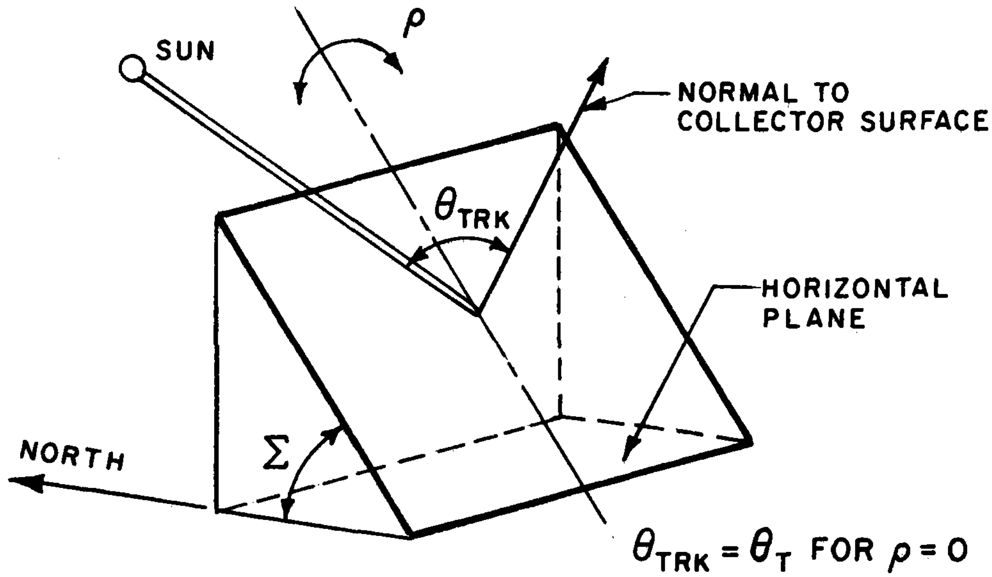

Figure B-6. Sun-Collector Geometry

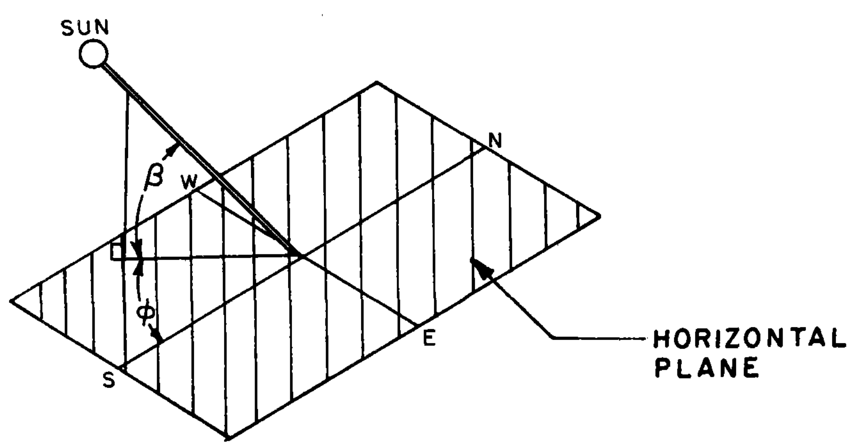

Figure B-7. Solar Azimuth and Altitude

LAT = latitude;

ϕ = solar azimuth angle;

ϕ = arc sin [cos(DEC) x sin(HRNO) $\div$ cos (β)] ;

β = solar altitude (Figure B-7);

β = 90-θ.

For a solar collector tracking the sun by rotating around an axis tilted through the angle Σ from a horizontal North-South line (Figure B-6), the incidence angle of solar radiation (θ_{TRK}) is given by

$$\cos(\theta_{TRK}) = \sin(\beta)\ (\cos(\rho)\ \sin(\Sigma)\ \cos(\phi) + \sin(\rho)\ \sin(\phi)) + \cos(\theta)\ \cos(\rho)\ \cos(\Sigma)$$

where (ρ) is the angle of rotation of the solar collector as it follows the East to West motion of the sun. This angle is zero when the solar collector faces due south and is positive for all other values of collector orientation. The optimum value of (ρ), i.e., the angle of rotation which maximizes the solar radiation incident on a fixed size of collector at any instant is obtained by differentiating the last equation with respect to ρ and setting the derivative equal to zero.

$$\rho_{max} = \arctan\left[\frac{\sin\beta\ \ \sin\phi}{(\sin\beta\ \ \sin\Sigma\ \ \cos\phi) + (\cos\theta\ \ \cos\Sigma)}\right]$$

The use of average solar radiation data for the analysis of a solar energy system can lead to significant errors. However, because Inyokern has relatively few cloudy days, the difference between the solar radiation available on an average day and on a clear day at this location is not nearly as significant as in other regions of the country. Consequently, the use of average solar data for Inyokern is justified and yields realistic results.

B-3.2 Energy Collected for Different Collectors and Orientation Methods

The energy which could be collected per square foot by each of the four solar collector types at Inyokern was calculated. Four methods of orienting the collectors were considered. In two of the methods, the collector position was fixed due south. In one case, the tilt angle (Σ) was also fixed, and in the other the tilt angle was adjusted on a monthly basis to maximize the solar input. In the other two methods of orientation, the collectors tracked the daily east-to-west motion of the sun, but the angle of rotation was limited to $\pm$ 45°. As before, in one case, the tilt angle (Σ) of the axis of rotation (Figure B-6) was fixed, in the other, the tilt angle was adjusted on a monthly basis. For each solar collector type and each method of orientation, the energy collected each month was calculated for several collector operating temperatures.

The results of this analysis are shown in Figures B-8 and B-9. It can be seen that a fixed position collector has the lowest output on an annual basis, and that a collector with east-to-west tracking and an adjustable tilt angle has the highest output. If the collector operating temperature is below 450°F, the Corning evacuated tube collector has the highest annual output. Above 450°F the CPC collector is the best performer. Although the Northrup and Chamberlain collectors have lower annual outputs at elevated operating temperatures, these two collectors may be more cost-effective at temperatures of 300°F or less because their costs are significantly lower.

A sawtooth array is the most likely configuration for a collector field used for solar feedwater heating. It was assumed that the collector rows would be spaced sufficiently far apart to minimize shading of one row by another. However, when east-to-west tracking is employed, it is not practical to separate each collector in a row such that no shading occurs. In the early morning and late afternoon each collector will be shaded to some extent by the collector to the East or West of it. This decreases the output of the total collector field. Beyond a certain angle of rotation (ρ) most of the available collector surface would be shaded. therefore the angle of rotation was limited to 45°. The extent to which

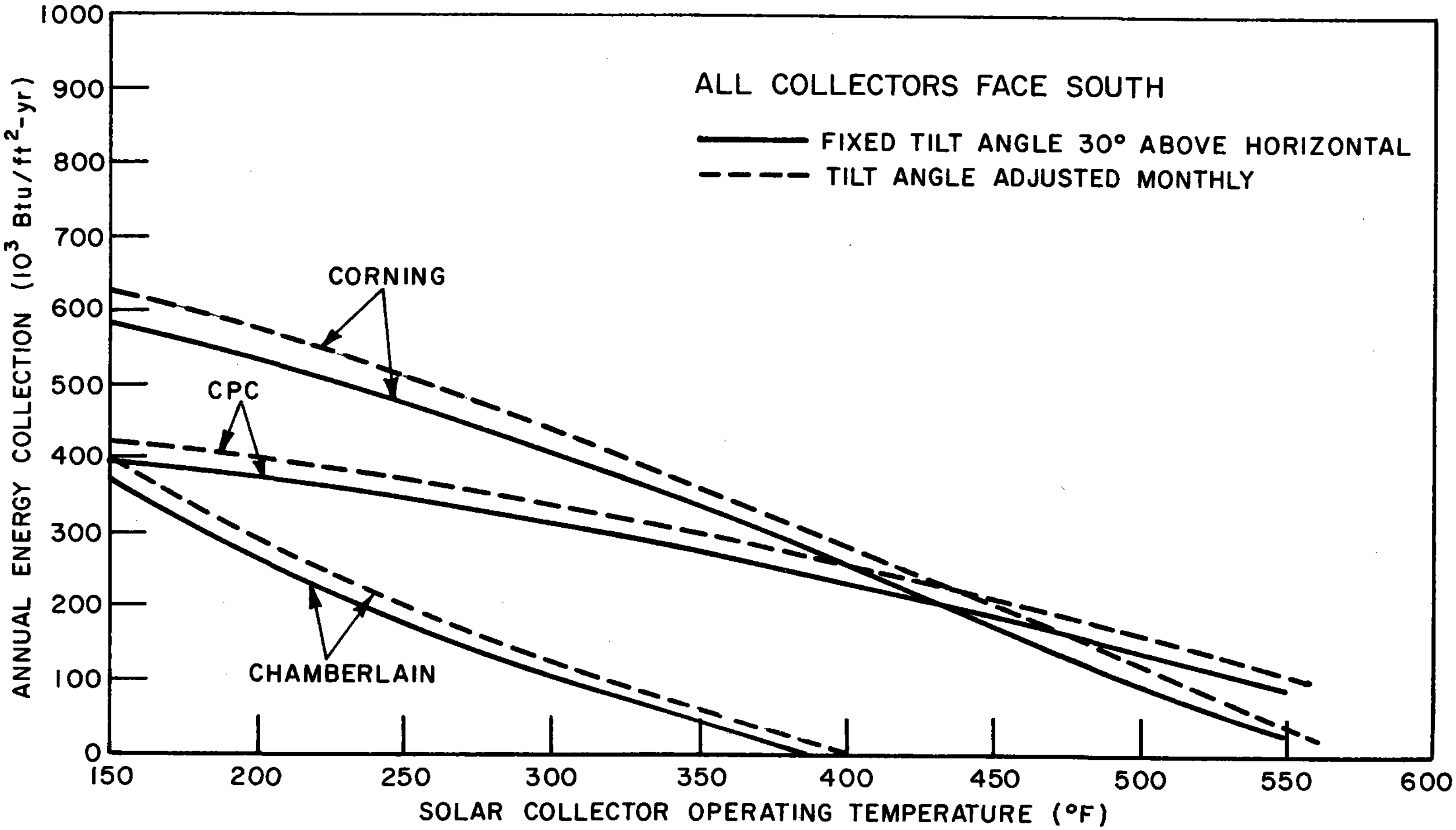

Figure B-8. Annual Energy Collection Rates for Fixed Collectors at Inyokern, CA

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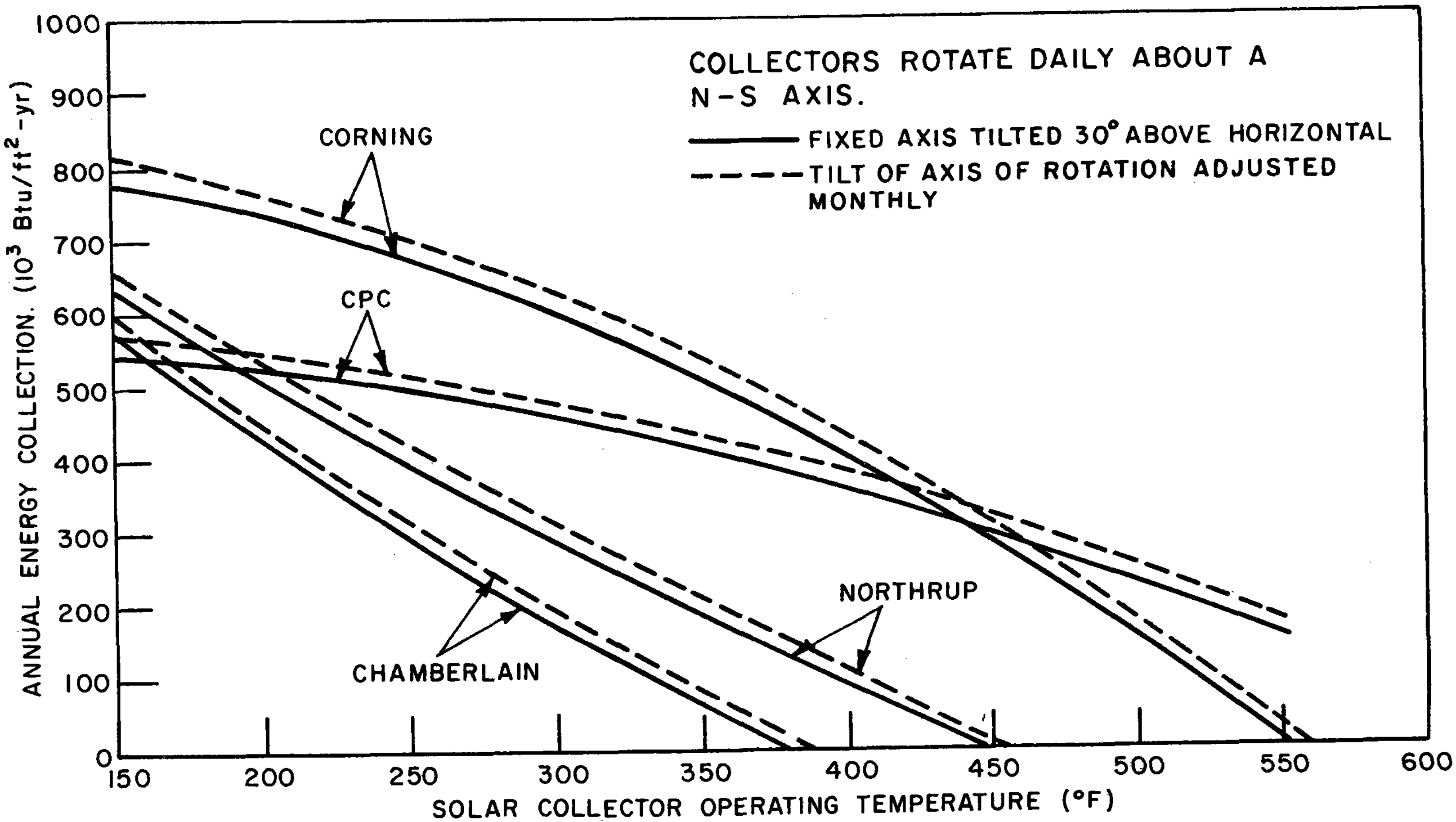

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Figure B-9. Annual Energy Collection Rates for Rotating Collectors at Inyokern, CA shading due to east-to-west tracking decreases the output from the array was not calculated. However, even though the curves in Figure B-9 are somewhat optimistic, a tracking collector collects significantly more energy than a fixed collector. This is illustrated in the table below which shows the monthly incident radiation on a fixed and a rotating (tracking) collector in Inyokern. For comparison, the monthly values for a fixed collector in Philadelphia, PA are also given.

Table B-1. Solar Radiation Incident on Collectors (Btu/ft^2)

Location	Philadelphia, PA	Inyokern, CA	
Collector Tilt Collector Azimuth	45° South	30° South	30° Tilt Axis Diurnal Rotation (Tracking Collector)
Jan.	40100	58600	68800
Feb.	38800	56300	71300
Mar.	46200	73900	93700
April	43400	78700	107700
May	60500	78800	104600
June	58000	76700	102900
July	54300	80600	107500
Aug.	51800	78800	106800
Sept.	47800	71400	91300
Oct.	45900	63200	79300
Nov.	39000	56300	66900
Dec.	29000	56600	65600
Annual	554,800	829,900	1,066,400

B.4 COSTS

A reasonably detailed analysis of the cost of the collector fields for different collectors and different methods of orientation was performed. Next to the cost of the collector modules themselves, piping accounts for the largest share of total costs. In order to evaluate that cost item properly, the actual geometry of the collector fields was established, and detailed piping costs were obtained from contractors.

The basic collector unit is shown in Figure B-10. It consists of a panel 46 ft wide and 22 ft high; it accommodates two horizontal rows of collectors having a total net area of 800 ft^2. This panel was designed to require a minimum of framing and foundation cost consistent with wind loads and servicing requirements. The same size panel would be used for either fixed or movable collectors. Figure B-10 illustrates a number of schemes for accomplishing monthly changes in tilt angle. A cost comparison showed that schemes 2 and 3 were approximately equal in cost, and scheme 1 was somewhat more expensive.

A basic collector field layout is shown in Figure B-11. It consists of two fields of 10 rows of 13 units each. Two rows are serviced by a common piping system of supply and return pipes. This collector field provides 208,000 ft^2 of net collector area. To determine the effects on costs of the collector field size, a field of 104,000 ft^2 (not shown) was also layed out. For each field, the flow rate through each pipe segment was established, and the required pipe sizes were determined. They are shown in Figure B-11. Unit costs for pipes are shown in Table B-2.

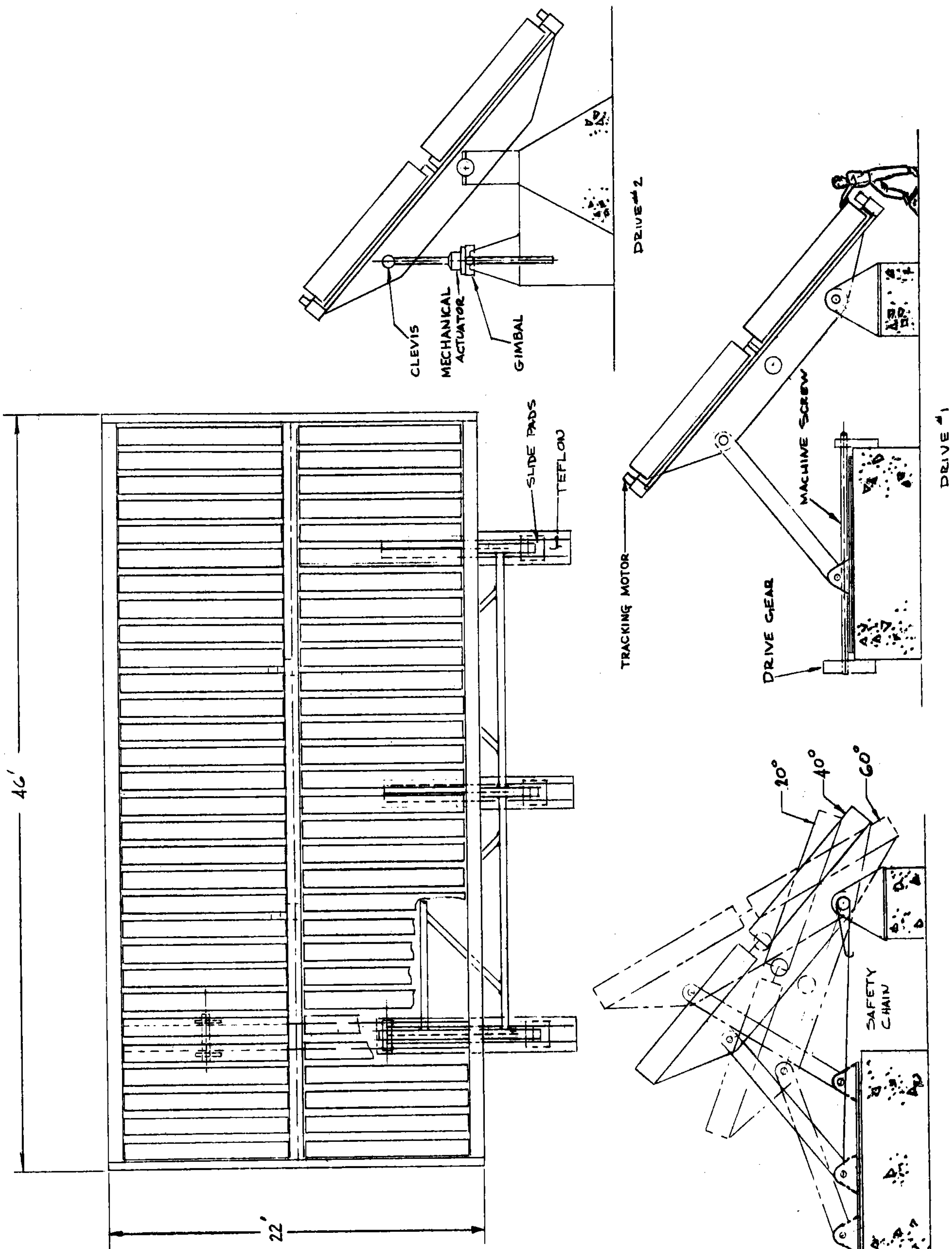

Figure B-10. Tilt Angle Adjustment for Fixed Collectors

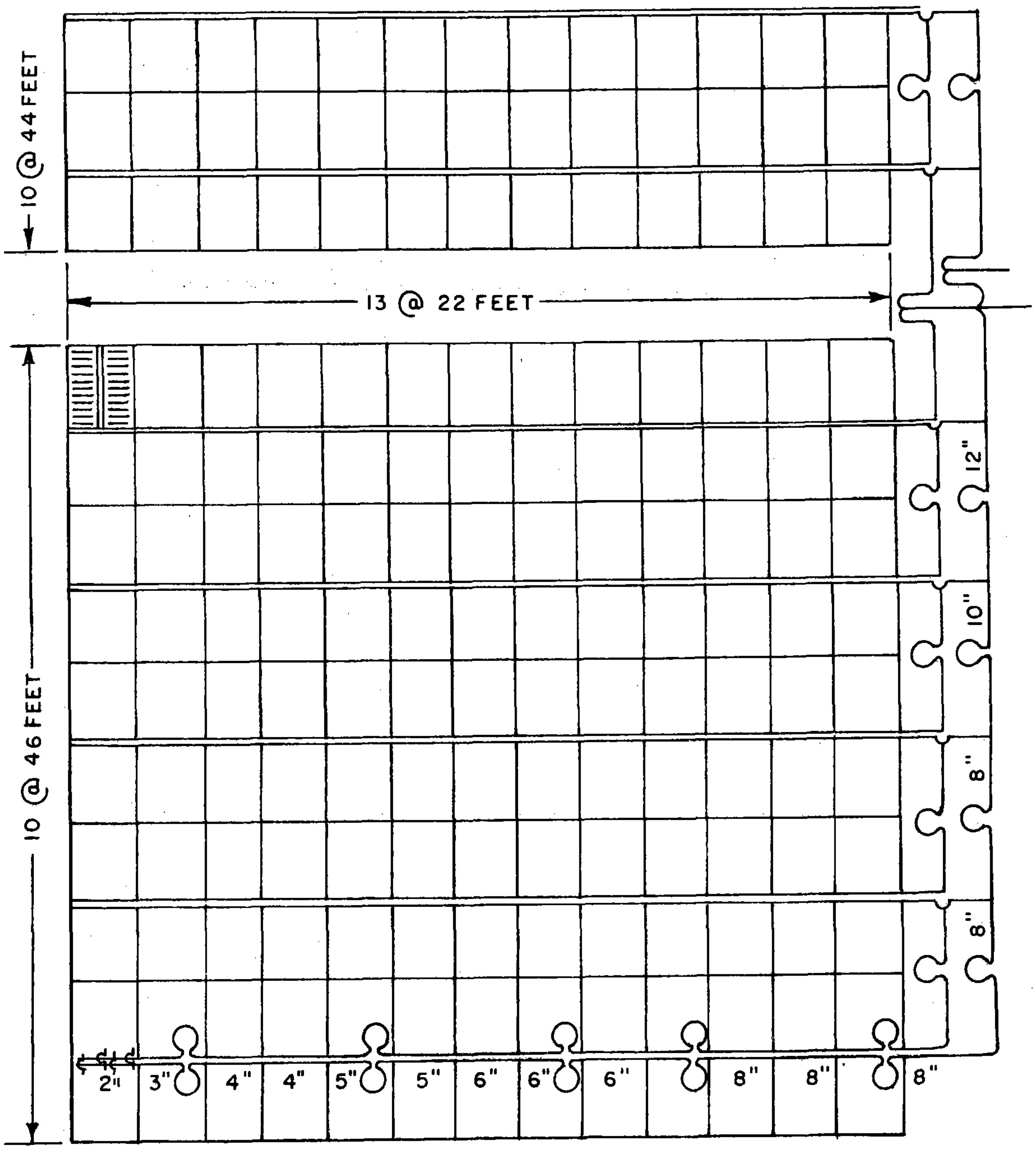

Figure B-11. Typical 208,000 Square Foot Solar Collector Field

Table B-2. Cost of Pipe Material

Nominal Diameter (inch)	Cost per Linear Foot ($/ft)	
	Schedule 40	Schedule 80
2	8.21	
3	10.52	
4	12.73	
5	15.69	
6	17.55	
8	23.16	
10		30.00
12	30.00	45.00
16		90.00

All cost components of the collector field were individually evaluated. A cost summary is shown in Table B-3. Column 2 shows total costs for a 208,000 ft^2 fixed collector field, column 3 for a 104,000 ft^2 field. The unit costs per square foot of net collector area for the smaller field are shown in column 4. Based on a collector cost of $\$12.00/ft^2$ for a flat plate collector, the total cost of solar augmentation for a 104,000 ft^2 collector field is $\$43.53/ft^2$. This includes cost of fixed collector modules and frames, foundations, piping, insulation, heat exchangers, pumps, valves, controls, instrumentation, installation of all items, connections to the existing power plant, contractors' contingency and profit, but excludes real estate costs.

Using the total cost for the larger collector field and dividing it by 208,000 ft^2 yields a unit cost of $\$43.33/ft^2$ for that field. The difference between these numbers is within the accuracy of the cost analysis, and a cost of $\$43.00/ft^2$ was used in the calculations in the main body of the report which were rounded off to the nearest $\$1.00/ft^2$.

Table B-3. Costs for Solar Augmentation, Flat Plate Collectors, No Rotation, High Pressure Piping*

	Total Costs ($)		Unit Costs ($ per ft^2 of Collector)	
Column Number	(2)	(3)	(4)	(5)
Collector Tilt	Fixed	Fixed	Fixed	{Adjusted Monthly}
Collector Field Size	208,000 ft^2	104,000 ft^2	104,000 ft^2	104,000 ft^2
Solar Collectors (Flat Plate, $12/$ft^2$)	2,496,000	1,248,000	12.00	12.00
Collector Support Frames	520,000	260,000	2.50	6.75
Collector Foundations	800,000	400,000	3.85	4.35
Subtotal, Collector Modules	3,816,000	1,908,000	18.35	23.10
Collector Fittings, Connections, Drains	575,860	287,937	2.76	3.26
Branch & Main Headers, Insulation, Anchors, Bends	362,640	158,353	1.52	1.52
Transmission and Station Piping	260,000	126,530	1.22	1.22
Subtotal, Piping & Insulation Material	1,198,500	572,820	5.50	6.00
Installation, 100%	1,198,500	572,820	5.50	6.00
Heat Exchangers	145,000	100,000		
Pumps	150,000	85,500		
Valves & Actuators	97,600	97,600		
Controls & Instrumentation	25,000	16,600		
Subtotal, Station Interface	417,600	299,700	2.88	2.88
TOTAL DIRECT COST	6,630,600	3,353,340	32.23	37.98
CONTINGENCIES, 10%	663,060	335,330		
ENGINEERING, 10%	663,060	335,330	11.30	13.30
G&A AND PROFIT, 15%	994,590	503,000		
GRAND TOTAL	8,951,000	4,527,000	43.53	51.28

*For low pressure piping, deduct $7/$ft^2$, see p. B-26.

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The unit costs for a 104,000 ft^2 collector field in which the collector tilt is adjusted monthly are shown in the last column of Table B-3. The major differences are increases in the cost of the collector framing (which includes the adjusting mechanism) and foundations, and an increase in the cost of connecting the piping to the collectors (which must permit motion). The total unit cost for this configuration is $51.28/$ft^2$, an increase of 17.5 percent over the unit cost of the same size collector field with fixed collectors.

It is apparent from Table B-3 that the cost of the flat plate collector modules themselves constitutes a relatively small part of the total cost of a solar augmentation. It accounts for approximately one-quarter of the total cost only. Unit costs for solar augmentation using other types of collectors are shown in Table B-4, rounded off to the nearest $1.00/$ft^2$.

Table B-4. Unit Cost Summary for Solar Augmentation Using Different Collectors and Orientation Methods (dollars per ft^2 of collector)

Collector Tilt Axis		Fixed	Adjusted Monthly	Fixed	Adjusted Monthly
Collector Rotation About Tilt Axis		None	None	Daily	Daily
Collector Type	Unit Cost				
Chamberlain	12	43	51	57	63
CPC	25	56	64	70	76
Corning	30	61	69	75	81
Northrup	14	-	-	45	53

Note: All figures are for high-pressure piping. Deduct $7/$ft^2$ for low pressure piping.

These costs were calculated by the following methods:

1. Collector Unit Costs were obtained from the manufacturers. For the Chamberlain and the Northrup collectors, these are firm costs for which collectors can presently be purchased in large quantities. For the Dow collector, this is the manufacturers estimate of costs in the near future when the collector will be commercially available. Since the CPC

collector is not yet in production, its cost was estimated based on the best available information after consulting with the developers of the concept and with manufacturers.

2. When collectors rotate about a tilted N-S axis to follow the daily motion of the sun (Fig. B-7), the east-west spacing of the collectors must be increased to avoid shading. If the rotation is limited to $\pm$ 45 degrees for mechanical reasons, the center-to-center distance of collectors must be increased approximately 50%. (Even that does not fully eliminate shading in early summer morning and late evening hours, but the energy lost from collector shading during those periods is small.) The resultant increase in 50% of the cost of the main headers amounts to $12,600 in additional material costs. Considering all the multipliers, this increases to $34,000 which equals $0.33/ft^2.

3. Rotating the 800 ft^2 collector unit about a single axis increases the cost of (1) the collector support frames, (2) the foundations, and requires (3) the addition of mechanical rotating devices and controls. If the tilt axis is fixed, this was assumed to add $2.50/ft^2, $1.50, and $6.00, respectively, to the unit costs of column 4, Table B-3. If the tilt axis is adjusted monthly, the additional cost increase is limited to the tilt mechanism. No further cost increases for framing and foundations occur because these components remain unchanged. That cost increase was calculated to be $4.25/ft^2.

4. The above cost figures were not arbitrarily chosen; they were estimated or calculated for one basic collector unit and then divided by the net collector area of the unit to obtain the numbers shown. After addition, all numbers were rounded off as previously explained.

All the costs up to this point were calculated on the basis of high-pressure piping which would be required if the boiler feedwater passes directly through the collectors after having been raised to a high pressure in a high pressure feedwater pump (see Fig. A-2). If the collectors are located on the low-pressure side of that pump, i.e., if they augment FWH Nos. 1 through 4 at temperatures below $\sim$ 300°F, low-pressure piping can be used. This results in a saving of $514,000 in direct costs for a 104,000 ft^2 collector field or a total saving of $694,000 = $6.66/ft^2. This amount should be deducted from the unit costs shown in Table B-4 in order to obtain the cost of solar augmentation below $\sim$300°F.