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Design Optimization for Solar Array of Multiple Collector Types

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DESIGN OPTIMIZATION FOR SOLAR ARRAY OF MULTIPLE COLLECTOR TYPES

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Abstract

Methodology is presented for optimizing solar arrays used for heating fluids from ambient to elevated temperatures. The optimal array consists of the appropriate combination of available collector types which delivers the most energy per dollar invested in the array. An example optimization is presented and verified using computer simulation of numerous combinations of collector types.

I. INTRODUCTION

A comprehensive design methodology for optimization of a solar collector was developed as part of an ERDA sponsored project, "Application of Solar Energy to Industrial Drying or Dehydration Processes." (ERDA Contract No. E-(40-1) -5121). (1) The methodology optimizes the combination of flat plate and focusing collectors to obtain output temperatures in the 150-200^{o}C range.

Commercially available collectors were compared using a "Cost-Effectiveness Index" (CEI). (CEI is defined as the collector efficiency divided by the installed cost of the collector in dollars per square foot of aperture). Plots of the CEI versus $\Delta T/H$ (the temperature differential between collector fluid and ambient temperatures, divided by the solar flux) were prepared for candidate collectors. These plots enabled the selection of the combination of collectors which provided the most cost-effective solar array. Preliminary calculations of optimal aperture areas for the selected collectors were made using seasonal averages for climatic conditions. The hourly performance of the array over the entire dehydration season was simulated using a modified version of the TRNSYS computer program. (2) TRNSYS simulations were also used to verify that the preliminary calculations of the array design resulted in the most cost-effective solar energy system.

The system design utilizes air as the heat transfer fluid. The selection of the type and area of each collector is based upon both the thermal and cost characteristics of each collector.

II. DESIGN METHODOLOGY

The choice of collectors is complicated by the functional variations of efficiency with ambient temperature, fluid temperature and insolation. An additional factor influencing the choice of collector is the installed cost per unit area of collector. If all collectors were the same price, the selection could be based entirely upon the expected energy collected under anticipated operating temperature and insolation levels. However, installed costs of different collectors vary widely. Therefore, the most cost-effective array may consist of an appropriate combination of both low efficiency, low cost collectors and high efficiency expensive collectors.

Assuming equal collector life times, the appropriate collector array for a particular application is composed of the set of available collectors yielding the highest CEI under typical operating conditions.

The first step in the design approach is to generate plots of CEI versus $\Delta T/H$ for commercially available air solar collectors. Next, based upon the average efficiency of each collector in its region of cost effectiveness, the average insolation and the mass flow to the collectors, the optimal area for each collector type is calculated. Consideration should also be given to the pressure drop across each collector and the cost of interfacing different collector types.

III. EXAMPLE OF OPTIMIZATION CALCULATION

In order to further illustrate the use of this design methodology for optimizing solar arrays, the following example is offered. This example is the design of a combustion air-preheating system for an alfalfa dehydration plant located in Lawrence, Kansas. The array design was based upon commercially available collectors utilizing air as the working fluid. The final collector array design consists of 304 flat plate collectors (5679 ft^2) manufactured by Sunworks and 38 focusing collectors (5804 ft^2) manufactured by Hexcel. The Sun Works collectors are mounted at 9.6 degrees above horizontal facing the south, while the Hexcel collectors are horizontally mounted on a north-south axis and track the sun from east to west.

Selection of Solar Collectors

Candidate solar collectors were compared on the basis of their cost effectiveness. A graphical method of comparison was used. Based upon manufacturer's data, plots of the CEI versus $\Delta T/H$ were prepared for candidate collectors. To develop the CEI versus $\Delta T/H$ plots, the efficiency of the collector as a function of $\Delta T/H$ was divided by the installed cost per square foot of collector. The cost used to calculate the CEI was the estimated installed cost per square foot of collector, including purchase cost, delivery cost, and all installation costs specific to the array. The estimated installed cost of the flat plate collectors was \$22.18/ft^2, while the cost of the concentrating collectors was \$28.82/ft^2.

Because the alfalfa dehydration process uses heated air as the drying medium, only solar collectors utilizing air as the heat transfer fluid were considered. This approach eliminates the need for freeze protection procedures and liquid-to-air heat exchangers, which are required for collectors that utilize liquids as the heat transfer fluid.

Over 30 collector manufacturers were contacted to provide performance data and cost information on their solar collectors. After a preliminary screening, five flat plate collectors were selected for detailed cost estimates. These collectors were manufactured by R-M Products Company, Solar Energy Products Company, Contemporary Systems, Inc., Sunworks and Solaron Corporation. Only one company, the Hexcel Corporation, was found that manufactured a focusing collector that could use air as the heat transfer medium. Detailed cost estimates were prepared for the Hexcel collector. By using the performance data supplied by the manufacturers, and the estimates of the installed cost per nominal square foot of collector area prepared by the project team, CEI versus $\Delta T/H$ plots were developed for the manufactured collectors.

Of the collectors evaluated, the Sunworks collector was found to be the most desirable flat plate collector. A high CEI, independent test data on the collector performance, high quality of materials and fabrication, and a sizable number of successful installations warranted the selection of the Sunworks collector over the other candidate flat plate collectors.

The Hexcel collector was the only focusing collector available that uses air as the heat transfer medium. Figure 1 shows that the CEI of the Hexcel collector is higher than the CEI of the Sunworks collector at values of $\Delta T/H$ above 0.41. This figure indicates that the most cost-effective solar array made up of commercially available collectors, and operating at values of $\Delta T/H$ above 0.41 would be a two-collector array of Sunworks and Hexcel collectors. Values of $\Delta T/H$ above 0.41 are necessary if the array is to make a significant contribution to the energy requirements of the dehydrator.

Calculation of Collector Areas for Array

Having selected the Sunworks and Hexcel collectors for use in the solar array, the orientations of these two collectors were specified. Subsequently, the optimal combination of areas of the Hexcel and Sunworks collectors in the array was determined. This section discusses the rationale for the specified orientations and the calculation of the aperture area of each of the collectors.

The Sunworks collectors are to be mounted at an angle of 9.6 degrees to the horizontal, tilted toward the south. A nearly horizontal mount was thought desirable for two major reasons. First, the zenith angle of the sun over the dehydration season approaches 90 degrees, and a tilted surface, therefore, does not intercept a significantly greater amount of radiation. Second, a nearly horizontal array of flat plate collectors is less expensive to construct than a tilted array. A slight tilt angle was ultimately chosen because this angle enabled a convenient connection between the flat plate and focusing collectors and permitted drainage of the flat plate array.

The Hexcel collectors are to be mounted horizontally along a north-south rotational axis. The collectors will track the sun from the east to the west. As in the case of the flat plate collector, a horizontal mount offered lower installation costs than a tilted mount, at no significant reduction in flux. A north-south axis of rotation was chosen because during the dehydration season, the flux on the north-south oriented, hourly tracking collector, is greater than an east-west oriented, elevation tracking collector.

The optimal area of the Sunworks collector was determined by calculating, under average operating conditions of the dehydrator, the area required to heat the incoming airlfow from ambient temperature to the temperature at which the Hexcel collector becomes more cost effective. In order to find this crossover temperature, plots of CEI versus the average temperature of the collector fluid were prepared for the two collectors.

To construct plots of CEI versus temperature, the average hourly values of the solar radiation over the dehydration season on the flat plate and focusing collectors were calculated. Figure 2 presents the results of these calculations. These seasonal, hourly values were again averaged to obtain a single average value of hourly radiation for each collector. The seasonal average radiation on the flat plate collector ($\overline{H}_T$) was calculated to be 180 Btu/ft^2/hr. The seasonal average radiation on the focusing collector ($\overline{H}_T$) was calculated to be 148 Btu/ft^2/hr. These radiation values were used to transform the x-coordinates of the efficiency versus $\Delta T/H$ plots of the two collectors to a temperature scale. The average daytime ambient temperature during the dehydration season is 75°F. Figure 3 shows the efficiencies of the Sunworks and Hexcel collectors as a function of average temperature of the collector fluid. The efficiency versus temperature plots were converted to CEI versus temperature plots by dividing the y-coordinates of the efficiency plots by the installed costs per square foot of the

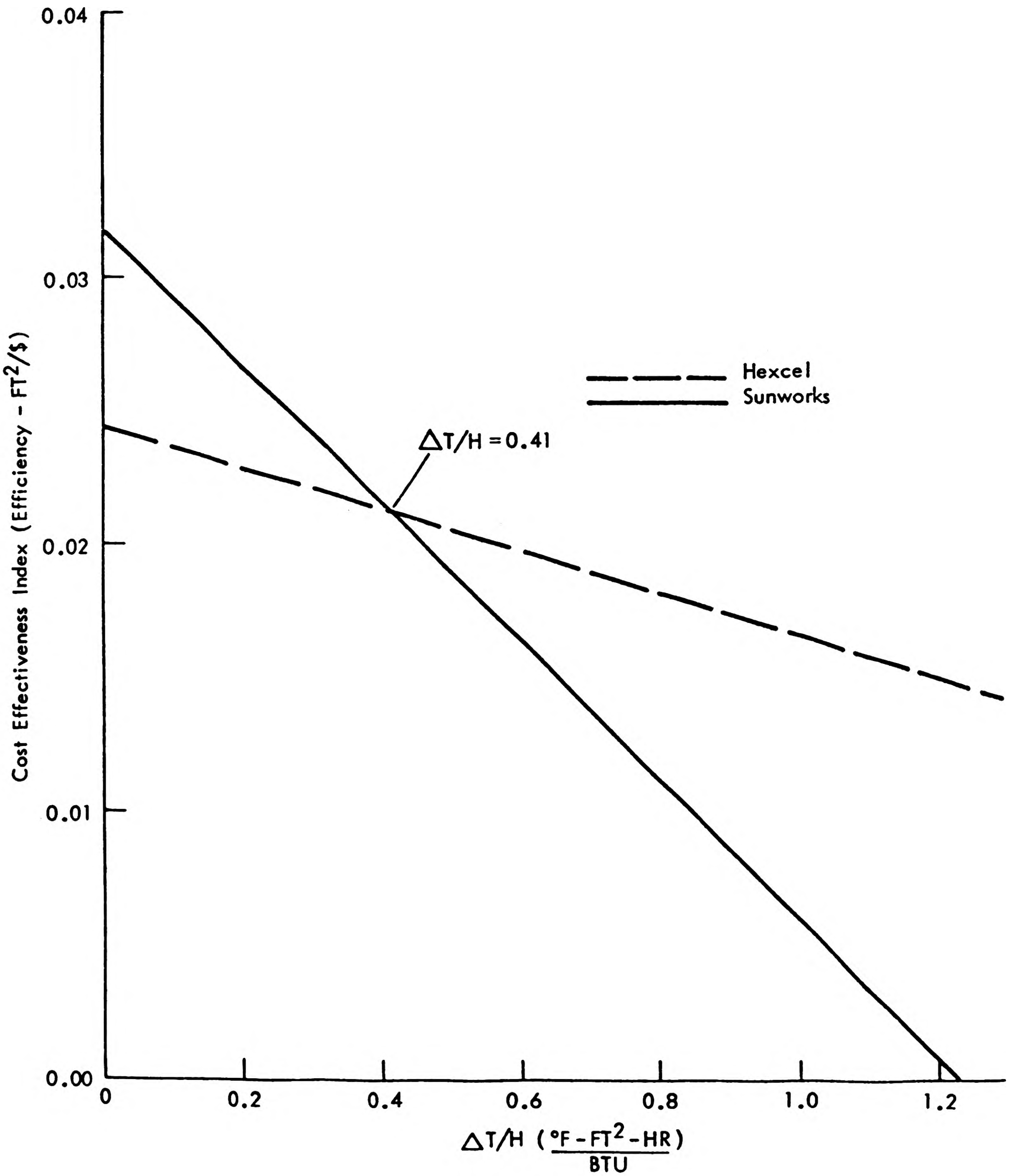

Figure 1 - Cost Effectiveness Index Versus ΔT/H Plots for Sunworks and Hexcel Collectors

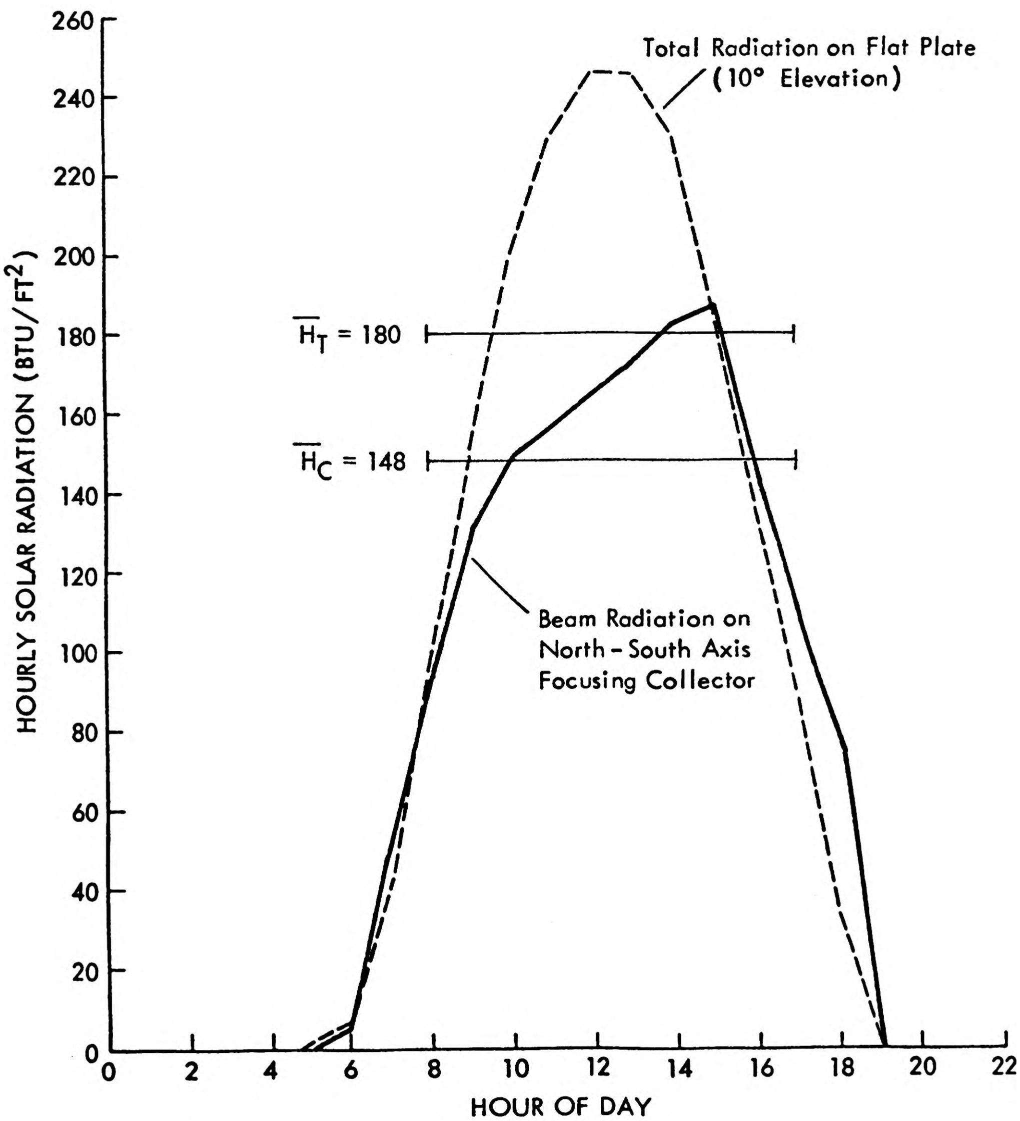

Figure 2 - Average Hourly Insolation During the Alfalfa Dehydration Season for Flat Plate and Focusing Collectors

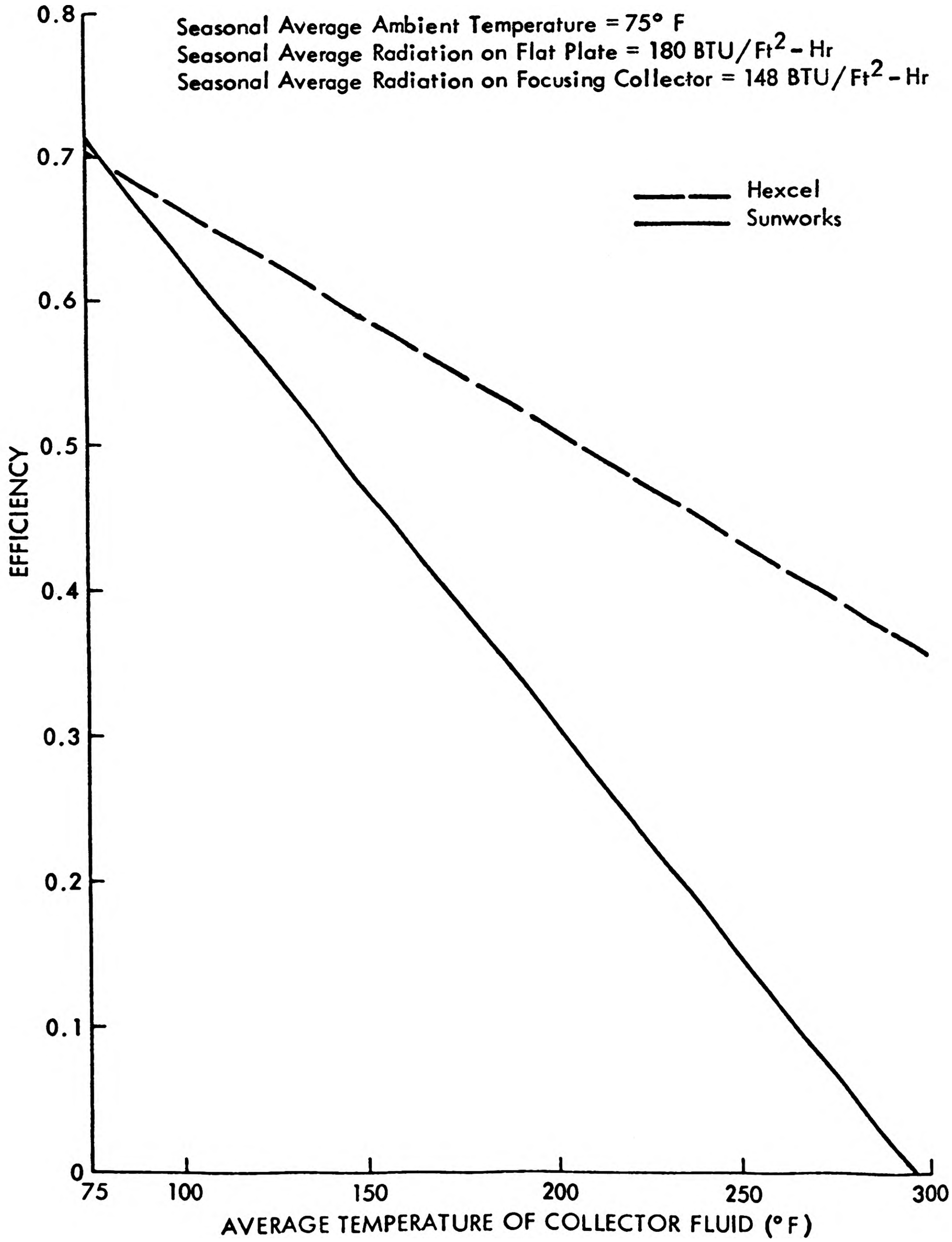

Figure 3 - Efficiency of Sunworks and Hexcel Collectors Versus Average Temperature of Collector Fluid

collectors. The CEIs versus average temperature of the collector fluid are graphed in Figure 4.

Figure 4 shows that at temperatures below approximately 157°F, the Sunworks collector is more cost effective than the Hexcel collector. The most cost effective array would therefore consist of a number of Sunworks collector sufficient to heat the airflow to 157.3°F under average operating conditions. Using the average flux level on the flat plate collector of 180 Btu/ft^2/hr, the average ambient temperature of 75°F, and the flow rate of 6,100 scfm (the flow rate required by the dehydrator), it was calculated that 5,324 ft^2 of aperture of Sunworks collector are required to heat the airflow to a temperature of 157°F. The following paragraphs describe the calculations used to determine the collector aperture area.

The optimal area of the Sunworks collector was determined by calculating the area required to heat the airflow of the dehydrator up to the temperature at which the Hexcel collector becomes more cost effective. The crossover temperature was found by driving the line equations of the CEIs for the two collectors and finding their intersection point. These equations are presented in Table I. The CEIs of the Sunworks and Hexcel are equal at a temperature of 157.3°F.

An energy balance equation was used to find the Sunworks area needed to heat the airflow of the dehydrator to 157.3°F. The energy added to the air as it passes through a bank of collectors is:

$$Q = MC_p\Delta T = \eta_{avg}HA \qquad (1)$$

where Q = energy added to airflow Btu/hr,
M = mass flow of air lbm/hr,
C_p = specific heat of air Btu/lbm,
ΔT = temperature increase of air through collector °F,
ηavg = average efficiency of the collector,
H = seasonal average solar radiation intensity Btu/ft^2-hr,
A = area of solar collector.

The area of Sunworks collector which would be most cost effective can be determined by solving equation (1) for A:

$$A = \frac{MC_p\Delta T}{\eta avgH} \qquad (2)$$

The mass flow through the dehydrator is equal to the airflow requirements of the dehydrator, 6,100 scfm, expressed as a mass flow, or 27,997 lbm/hr. The specific heat of air at standard conditions is 0.24 Btu/lbm. The temperature increase of air through the collector is equal to the output temperature minus the ambient temperature or:

$$157.3°F - 75°F = 82.3°F \qquad (3)$$

TABLE I

EQUATIONS FOR EFFICIENCY AND CEI VERSUS TEMPERATURE PLOTS

Assumptions:

Average Ambient Temperature During Dehydration Season = 75°F

Average Total Radiation on Flat Plate Collector During Dehydration Season = 180 Btu/ft^2-hr

Average Beam Radiation on Focusing Collector During Dehydration Season = 148 Btu/ft^2-hr

Sunworks:

η = 0.71 - 0.00323 (T - 75)
CEI = 0.032 - 0.000145 (T - 75) (assumes installed cost of \$22.18/ft^2)

Hexcel:

η = 0.705 - 0.001538 (T - 75)
CEI = 0.0245 - 0.000053 (T - 75) (assumes installed cost of \$28.82/ft^2)

ηavg for the Sunworks collector was found by substituting the output temperature, 157.3°F, into the Sunworks efficiency equation (Table I)

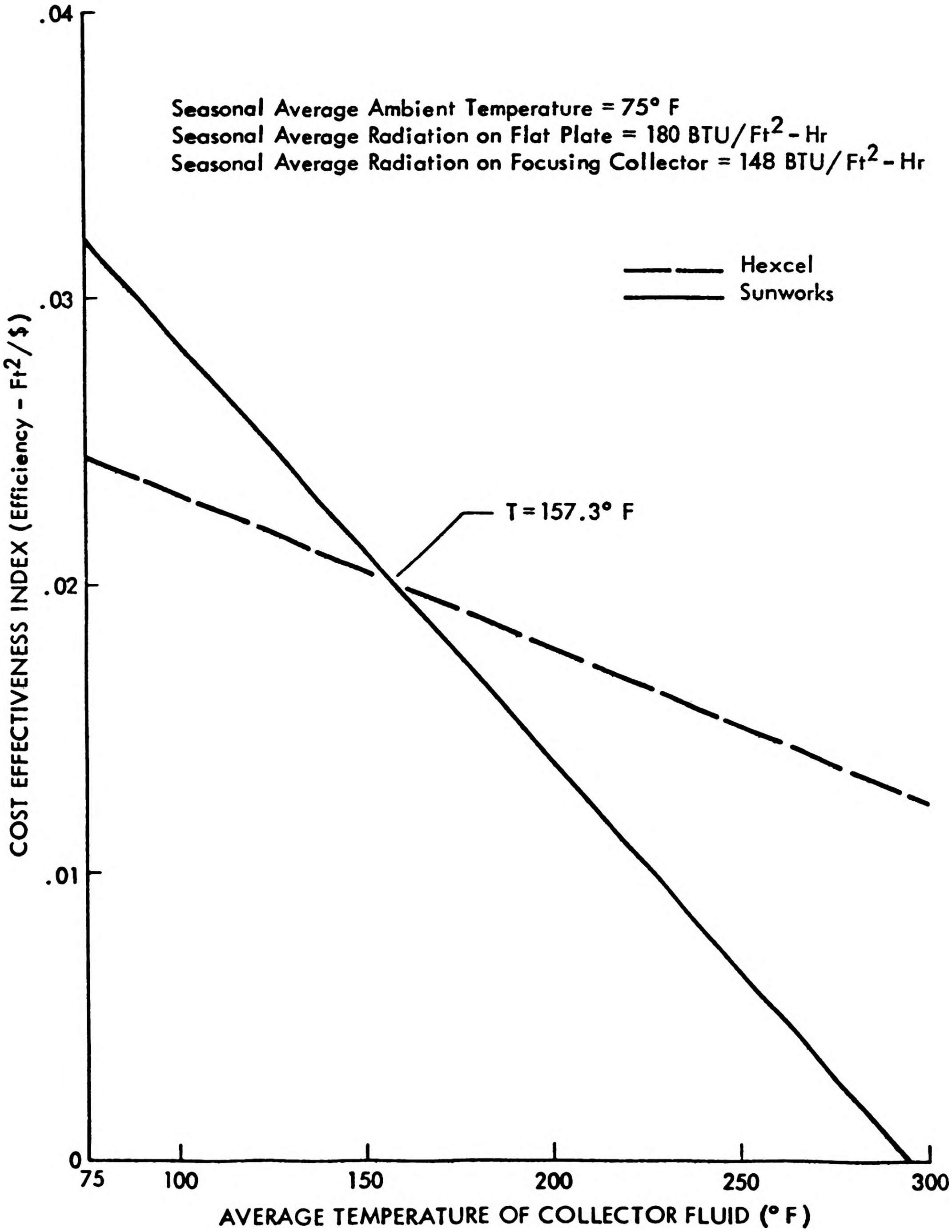

Figure 4 - Cost Effectiveness Index Versus Average Temperature of Collector Fluid for Sunworks and Hexcel Collectors

and averaging this value with the efficiency at the ambient temperature, 75^oF:

$$\eta_{avg} = \frac{\eta_{75} + \eta_{157.3}}{2} = \frac{0.71 + 0.444}{2} = 0.577 \quad (4)$$

The intensity of the seasonal average solar radiation on the Sunworks collector tilted at a 10 degree angle, is 180 Btu/ft^2--hr. Substituting these values into equation (2) yields:

$$A = \frac{(27,997)\ (0.24)\ (82.3)}{(0.577)\ (180)} = 5,324\ ft^2$$

The optimal area of Hexcel collectors in the array was indeterminant because, at all output temperatures above 157.3^oF, the Hexcel collector is the most cost-effective collector. The absolute upward limit of the area of the Hexcel collector would be the area required to heat the air from the output temperature of the Sunworks collectors, (157.3^oF), to the operating temperature of the dehydrator. Space availability and the availability of funds, however, proved to be more limiting constraints. Another consideration in choosing the area of Hexcel collectors was the pressure drop through the receiver tube of the focusing collector. It was necessary to have enough Hexcel collectors in parallel so that the pressure drop through the receiver tube would not be excessive. Calculations showed that a minimum of 19 collectors in parallel resulted in acceptable pressure drop.

A final consideration in determining the optimal area of Hexcel collectors was that there are economic benefits to having collectors connected in series. The same tracking mechanism can drive a number of collector in series. The cost of the tracking mechanism, therefore, can be distributed over a larger aperture area, resulting in a more cost-effective array. Accounting for all of these factors, 38 Hexcel collector modules or 5,804 ft^2 of Hexcel collector aperture area were specified in the array design. Nineteen parallel rows of two Hexcel collector modules connected in series were specified as the layout of the Hexcel collectors on the dehydration plant site.

Consideration of the layout of the collector array on the plant site indicated that installation of Sunworks collectors in rows of 38 modules would provide a convenient interface to the 19 parallel rows of Hexcel collectors. The calculated optimal aperture area for the Sunworks collector, 5,324 ft^2, represents 7-1/2 rows of 38 collectors per row. It was felt that a half row of collectors in the array would not be advisable. Therefore, the optimal area of 5,324 ft^2 was rounded up to 5,629 ft^2 or to eight rows of 38 collector modules for a total of 304 Sunworks collector modules. This extra area of Sunworks collectors is only a small increase from the calculated optimal area, and should have an insignificant impact on the overall cost effectiveness of the operation of the collector array.

In conclusion, calculations of the optimal area of Sunworks collector and consideration of the layout of the collector array on the plant site are determined the specified areas of the two collectors in the array. These dimensions are summarized in Table II. The total aperture area of the preliminary array design is 11,483 ft^2.

TABLE II

PRELIMINARY CONFIGURATION OF COLLECTOR ARRAY

	Aperature Area of Collector	Number of Collector Modules
Sunworks	5,679 ft^2	304
Hexcel	5,804 ft^2	38

IV. VERIFICATION OF DESIGN METHODOLOGY TRNSYS SIMULATION

After the preliminary calculations of the optimal areas of the Sunworks and Hexcel collectors were completed, the TRNSYS program was used to simulate the hourly performance of the array design over the dehydration season. A sensitivity analysis of other combinations of areas of the Sunworks and Hexcel collectors was performed using TRNSYS simulations to verify that the specified preliminary array design was, in fact, the optimal design.

In order to simulate the hourly performance of the array over the dehydration season, a composite year of hourly insolation and weather data for Columbia, Missouri, was developed. (Solar radiation data are not available for Lawrence, Kansas). Although the Columbia radiation data may understate the radiation in Lawrence, Kansas, by 10 to 15%, it was felt that the Columbia data are the best available for system design and optimization.

Two modifications of the TRNSYS programs were made in order to simulate the performance of the focusing collector. First, the program was modified to derive hourly values of the beam radiation incident on the focusing collector from the available data, the hourly total radiation on a horizontal surface. Second, changes were made to account for the end losses of the focusing collector as a function of the incidence angle of the beam radiation.

The TRNSYS simulations were set up so that the entire airflow requirements of the dehydrator, 6,100 scfm passed first through the flat plate collectors and then into the focusing collectors. All parameters affecting the efficiency of the flat plate and focusing collectors were entered into the program. Losses in the array air ducts were accounted for by slightly overstating the loss coefficients of the concentrating collectors.

The TRNSYS simulations were used to produce integrated values of the energy output of the array over one dehydration season. In addition to simulating the energy output of the preliminary array design, four other simulations were performed for arrays with different combinations of flat plate and focusing collectors. The total seasonal energy output for each array was then divided by the total cost of the array to yield a seasonal value for the energy output of each array per dollar invested. The results of this sensitivity analysis are summarized in Table III. A graph of the energy output per season per dollar of capital cost as a function of the ratio of the area of focusing collector in the array to the total area of the array is shown in Figure 5.

The optimal combination of flat plate and focusing collectors is that combination which yields the maximum energy output per season per dollar of capital cost. It can be seen from Table III and Figure 5 that the preliminary array design (area focusing/area total = 0.505) is significantly more cost effective than an array made up of either all flat plate or all focusing collectors. Examination of Figure 5 shows that the optimal combination of flat plate and focusing collectors is between a ratio of area of focusing collector to total area of 0.25 (aperture area Sunworks = 8,612 ft^2, aperture area Hexcel = 2,871 ft^2) and the area ratio at the preliminary design point, 0.505.

The curve of kilojoules collected per season, per dollar capital cost as a function of the focusing area to total area ratio appears to be relatively flat between 0.25 and 0.505, the design ratio. Although Figure 5 indicates that the maximum energy output per dollar would occur with an array made up of more flat plate collectors than in the preliminary array design, the difference in cost effectiveness would appear to be minimal.

No modification of the preliminary array design was made as a result of this sensitivity analysis. While an array with more Sunworks collectors appears to be marginally more cost effective than the preliminary design, it was believed that the savings realized by a revised design did not warrant modification. The Columbia, Missouri, weather data used in the simulation understates the direct radiation on the focusing collector to be located in Lawrence, Kansas. The simulation therefore, underestimated the energy out-

TABLE III

SENSITIVITY ANALYSIS OF ENERGY OUTPUT PER SEASON PER DOLLAR OF CAPITAL COST FOR DIFFERENT AREAS OF SUNWORKS AND HEXCEL COLLECTORS

Area Total = 11,483 sq ft

Area Focusing / Area Total	0.0	0.25	0.505 (Design)	0.75	1.00
Area Flat Plate at $22.18/sq ft*	11,483 sq ft	8,612	5,679	2,871	0
Cost of Flat Plate	$254,693	$191,014	$125,960	$ 63,679	0
Area of Focusing at $28.82/sq ft*	0	2,871	5,804	8,612	11,483
Cost of Focusing	0	$ 82,742	$167,271	$248,198	$330,940
Total Variable Cost	$254,643	$273,756	$293,231	$311,877	$330,940
8,000 CFM Fan System and Duct Work	$ 14,400	$ 14,400	$ 14,400	$ 14,400	$ 14,400
Electrical Controls and Monitoring	$ 3,000	$ 3,000	$ 3,000	$ 3,000	$ 3,000
Total Cost	$272,093	$291,156	$310,631	$329,277	$348,340
10^9 KJ/Season	1.9	2.09	2,23	2,27	2.2
KJ/Season - $ Cost	6,983	7,178	7,179	6,894	6,316

* Estimated installed cost of solar collector array.

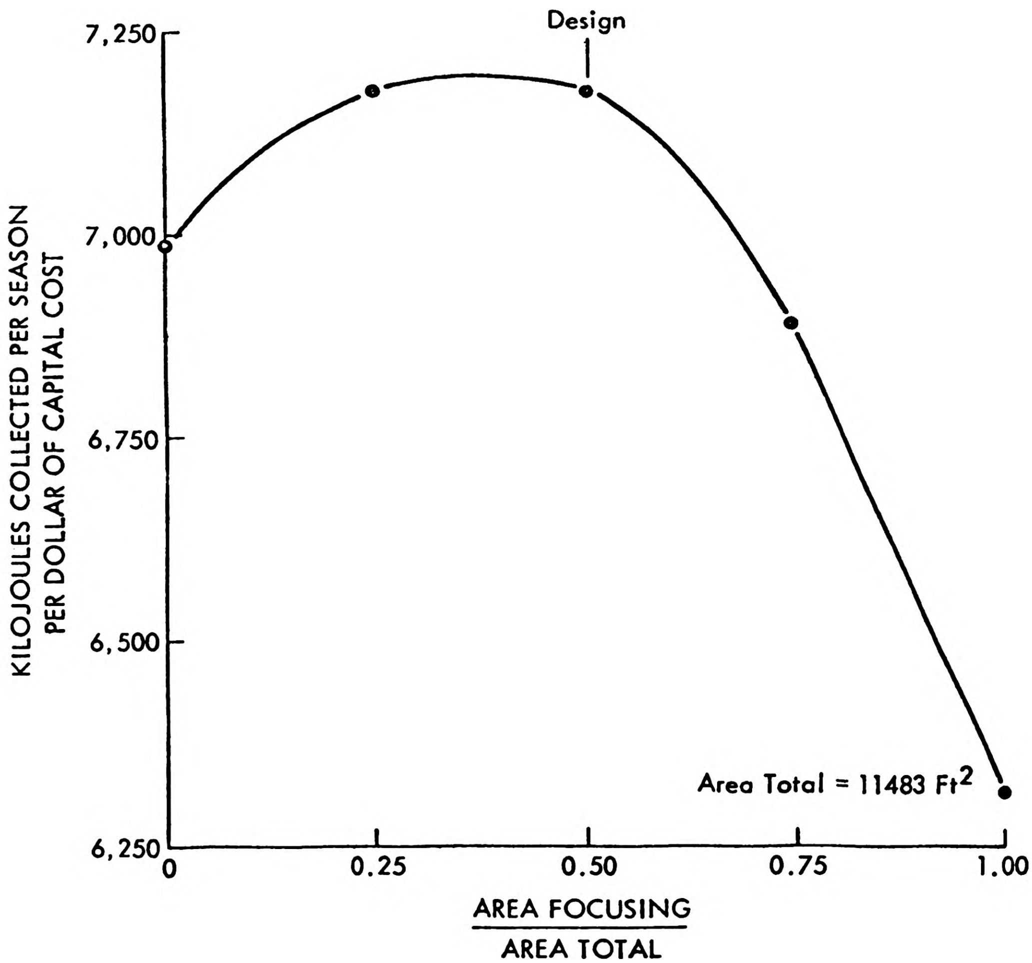

Figure 5 - Sensitivity Analysis of Energy Output Per Season Per Dollar of Capital Cost for Different Areas of Sunworks and Hexcel Collectors

put of the concentration array and appears to reduce the desirability of using less focusing collector area.

The results of this design process indicate that a two-collector array made up of 304 Sunworks flat plate collectors and 38 Hexcel focusing collectors is potentially the most cost-effective solar array. These collector areas were used in the preparation of all detailed engineering drawings and specifications of the solar energy system.

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BIOGRAPHIES

Jerry Bradley is currently Director of the Energy Systems Center of the Desert Research Institute located in Boulder City, Nevada. The Energy Systems Laboratory is involved in research and development relating to various energy systems with special emphasis upon solar. Mr. Bingham and Mr. Posner are members of the Technical Staff of the Solar Energy Research Institute located in Golden, Colorado. The Solar Energy Research Institute is operated for the United States Department of Energy by Midwest Research Institute.