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ANALYSIS OF COLLECTOR ARRAY PERFORMANCE FROM FIELD DERIVED MEASUREMENTS

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Analysis of Collector Array Performance
from Field Derived Measurements

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ABSTRACT

The Hottel-Whillier-Bliss (HWB) equation has been the standard tool for evaluation of collector thermal performance for many years. This paper presents a technique which applies the criteria of ASHRAE Standard 93-77 to the determination of the HWB equation coefficients using measured performance of actual collector arrays in a field environment. Results of the analysis of an example collector array illustrate the technique. Finally, preliminary results of the analysis of a number of collector designs are presented.

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INTRODUCTION

The National Solar Energy Demonstration Program is collecting and archiving data measured at operating solar-energy systems. These systems represent heating, cooling and hot-water applications to residential, commercial, and industrial facilities.

The availability of these data provides an opportunity to verify the practicality of design concepts and tools which, prior to now, were the province of laboratory scientists. One such tool is the industry standard collector model, the Hottel-Whillier-Bliss (HWB) equation.

This paper presents a technique by which the field performance of collector arrays is related to the HWB equation via ASHRAE Standard 93-77, which established technical criteria for collector evaluation. An example array, located in the north central, Great-Plains Area, is used to illustrate the technique. Preliminary results of the analysis of three collector designs are presented.

COLLECTOR ARRAY EFFICIENCY

The steady-state thermal performance of a single flat-plate collector is well understood, and has been the subject of a number of technical papers over the past four decades (Refs. 1-6). Rigorous thermal performance calculations involve the iterative solution of nonlinear matrix equations of rank 5 or higher. To avoid this complexity, the industry has adopted the HWB equation (Ref. 2) as its standard tool for steady-state collector evaluation.

$$Q_u = F_R A \left[I \ (\tau\alpha)_e - U_L \ (t_{f,i} - t_a) \right] \qquad (1)$$

The elements of the HWB equation are the absorber plate area, A; the insolation level, I; the effective product of the cover transmissivity and the plate absorptivity, $(\tau\alpha)_e$; the collector loss coefficient, U_L; the fluid inlet temperature, $t_{f,i}$; ambient temperature, t_a; and a collector heat removal factor, F_R. The principal inaccuracy of the HWB equation lies in the assumption that U_L is constant; whereas, in reality, U_L is a strong function of wind and temperature. The usual method of collector evaluation is to set up steady-state laboratory test conditions and measure energy gain from the equation:

$$Q_u = \dot{m}\, C_P\, (t_{f,e} - t_{f,i}) \tag{2}$$

where $\dot{m}$ is the mass flow rate, C_P is the working fluid specific heat, and $t_{f,e}$ is the fluid exit temperature. Setting Eq. 1 equal to Eq. 2 and solving for the ratio of actual energy collected to the incident energy leads to

$$\eta = Q_u/IA = F_R\, (\tau\, \alpha)_e - F_R U_L\, (t_{f,i} - t_a)/I \tag{3}$$

Q_u is calculated from the available measurements and material properties by Eq. 2, and the expression $(t_{f,i} - t_a)/I$ is formed from measured quantities, leaving $F_R\ (\tau\alpha)_e$ and $F_R U_L$ as unknowns.

An expression of the form of Eq. 3 can be graphed as a straight line having the intercept, $F_R\ (\tau\, \alpha)_e$, and the slope, $F_R U_L$, on a coordinate system that has $(t_{f,i} - t_a)I$ as the abscissa and η as the ordinate. This provides a convenient basis for comparison of various collector configurations. Toward that objective and for reasons of consistency, ASHRAE Standard 97-77, "Methods of testing to Determine the Thermal Performance of Solar Collectors", was released in 1977 (Ref. 7).

Briefly described, the collector testing guidelines of ASHRAE 93-77 require testing to be accomplished under the following conditions: (1) a steady state collector temperature environment; (2) insolation greater than 200 Btu/ft^2hr; (3) wind speed less than 10 mph; and (4) a range of ambient temperature of less than 55 degrees during the testing. A minimum of 16 efficiency points are required.

The test method of ASHRAE 93-77 is to establish steady-state conditions of flow, irradiation, exit temperature, and ambient temperature for several values of inlet temperature (the controlled variable); then, calculate efficiency, η , from equation (3) and plot the resulting points. A line is then drawn through the points, using a first-order, least-square curve fit. A typical test result is illustrated in Figure 1.

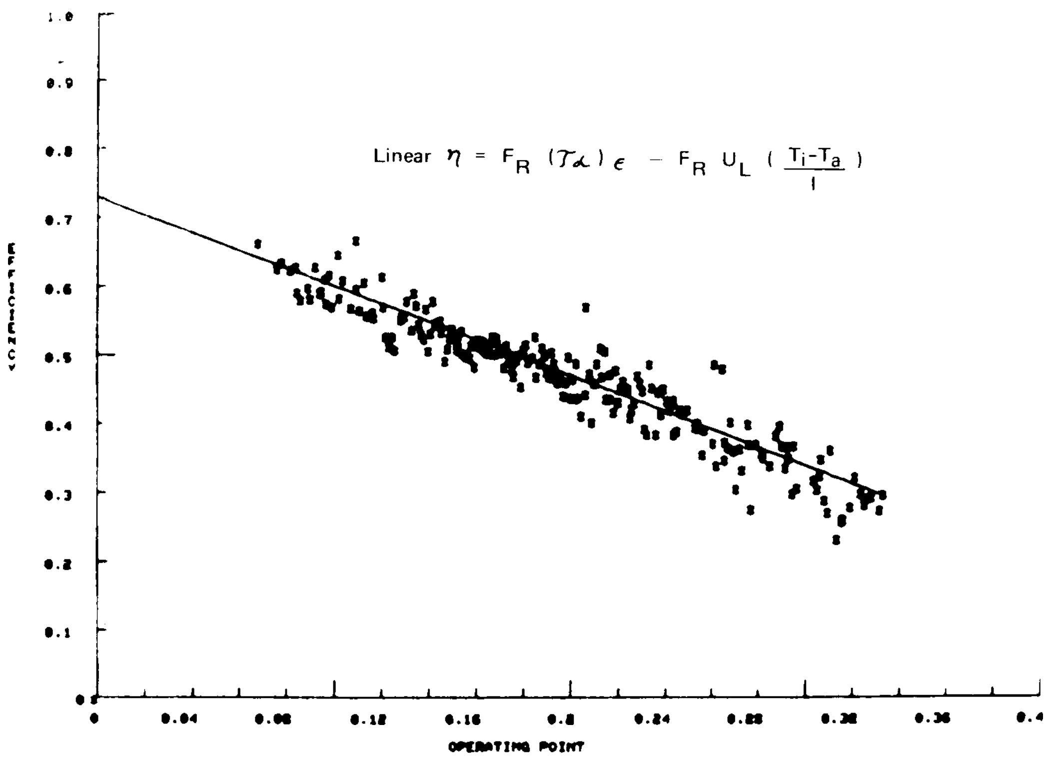

Figure 1. Typical Test Result

The extension of single-collector performance expectations to an array expectation requires assumptions, since the single collector analysis does not take into account the working fluid held in the external manifolding and risers. For an array of more than one, or two collectors, the working fluid held external to the collector panels becomes significant. Also, it is noted that the ASHRAE "steady-state" requirement is equivalent to requiring a zero propagation time between a change in fluid-inlet conditions and the effect on the fluid-outlet conditions. Since collector arrays in the field are exposed to a variety of dynamic forcing functions, (clouds, wind, diurnal variations in sunlight, shading, etc.), the expectation is that steady-state conditions will never be observed.

The effect of the fluid mass between inlet and outlet temperature sensors is to delay the propagation of transient effects, resulting in a large degree of scatter in the derived information points. To partially compensate for this effect, the energy-gain equation is modified to include stored, internal energy.

Consider implementation of the ASHRAE collector thermal analysis procedure in a system which acquires time-coherent data points at equally spaced intervals. A time-coherent group of measurements is called a "scan". The measured parameters are $\dot{W}$, the fluid volumetric flowrate; $t_{f,e}$, fluid exit temperature, $t_{f,i}$, fluid inlet temperature, t_a, ambient temperature; and I, insolation level. The fluid specific heat, C_p, may be calculated from its material properties. The fluid mass, M, between inlet and outlet temperature sensors is a measured constant. Volumetric flow rate, $\dot{W}$, is converted to mass flowrate, $\dot{m}$, through multiplication by the fluid density, ρ, and a flow-correction factor, f_c.[1] Then, for computation of the abscissa, we write

$$X = (t_{f,i} - t_a)/I \qquad (4)$$

and for computation of the ordinate, we write

$$\eta = \dot{m}\, C_p\, (t_{t,c} - t_{f,i})/IA + MC_p\, (\Delta t_{avg})/T \qquad (5)$$

where Δt_{avg} is the change in the average fluid temperature over the scan period, T.

It was assumed in the derivation of Eqs. 4, 5 that the input measurement data is representative of steady-state thermal operation. However, field derived measurements are dynamic and include transient thermal effects. In order to meet the "steady-state" requirements of ASHRAE 93-77 and to utilize the HWB equation, constraints must be placed on the field-derived data. These constraints typically take the form of limitations on magnitude, and limitations an allowable variation with time. In the process of evaluating field performance of collector arrays, the application of constraints is referred to as "filtering".

[1] C_p, ρ, and f_c are calculated functions of the fluid temperature at the point of flow measurement.

FILTERING

The filtering process attempts, as closely as practical, to adhere to the philosophy and procedures outlined in ASHRAE Standard 93-77. To accomplish this, eight filters were designed to effectively impose and implement the restrictions associated with quasi-steady-state operating conditions. These filters are:

- Sun angle maximum
- Insolation floor
- Insolation variation between scans
- Wind velocity ceiling
- Inlet temperature variation between scans
- Temperature gain variation between scans
- Ambient temperature variation between scans
- Flowrate variation between scans.

where a scan is one time-coherent group of measurements.

The capability has been provided to choose the number of scans (5-min., 20-sec. periods) over which variation constraints are imposed. A brief description of the use of the filters is given below.

The isolation floor filter establishes a variable lower limit on the insolation. It is nominally set for 200 Btu/hr-ft^2, may be adjusted as required for the collector array design.

The sun-angle constraint is required in order to exclude reflection effects at low angles of incidence and to compensate for collector array orientations which do not face due south. When flat-plate collectors are evaluated, it is desirable to exclude all data points beyond 30 degrees of the collector normal. However, tracking collectors and tubular collectors operate well at higher angles, and the sun-angle filter limit is increased correspondingly.

A ceiling is placed on the wind velocity. The principal error source of the HWB equation lies in the variation of U_L with wind and temperature. Since the wind filter is adjustable in the software, the exact effect on U_L may be characterized for a given array. Control of the wind effects, through filtering, reduces point scatter considerably.

After the raw scan data has passed the limiting filters, the search begins for steady-state conditions. Examination of Eqs. 4, 5 reveals that flow, fluid-inlet temperature, fluid-exit temperature, ambient temperature, and insolation level enter into the determination of a point on the $X-\eta$ coordinate system. These are the measurements which must be held nearly constant for a period of time greater than the time constant of the collector in order to establish steady-state.

EXAMPLE RESULTS

The performance analysis of collectors from field derived measurements is an experimental technique now under development and evaluation. The following results must, therefore, be considered preliminary.

Figure 2 is the initial scatter diagram derived by applying Eqs. 4, 5 to raw, unfiltered data from an aluminum absorber - copper tube collector array. Application of a 10 mph ceiling on the wind velocity reduces the scatter to a much narrower band, as shown in Figure 3. Figure 4 is the scatter diagram of the points remaining after setting the sun-angle filter to 30 degrees and variation filters to 5 percent over one scan (320 seconds). A regression line has been plotted through the points, from which the slope and intercept are found to be -0.303 and 0.815, respectively.

Figure 5 is the initial scatter diagram for a lexan glazed - steel/aluminum absorber collector array. Figure 6 is the efficiency curve derived from raw data by the filtering process and curve-fit. Note the coefficients deviated less than 5 percent between filtered and unfiltered data.

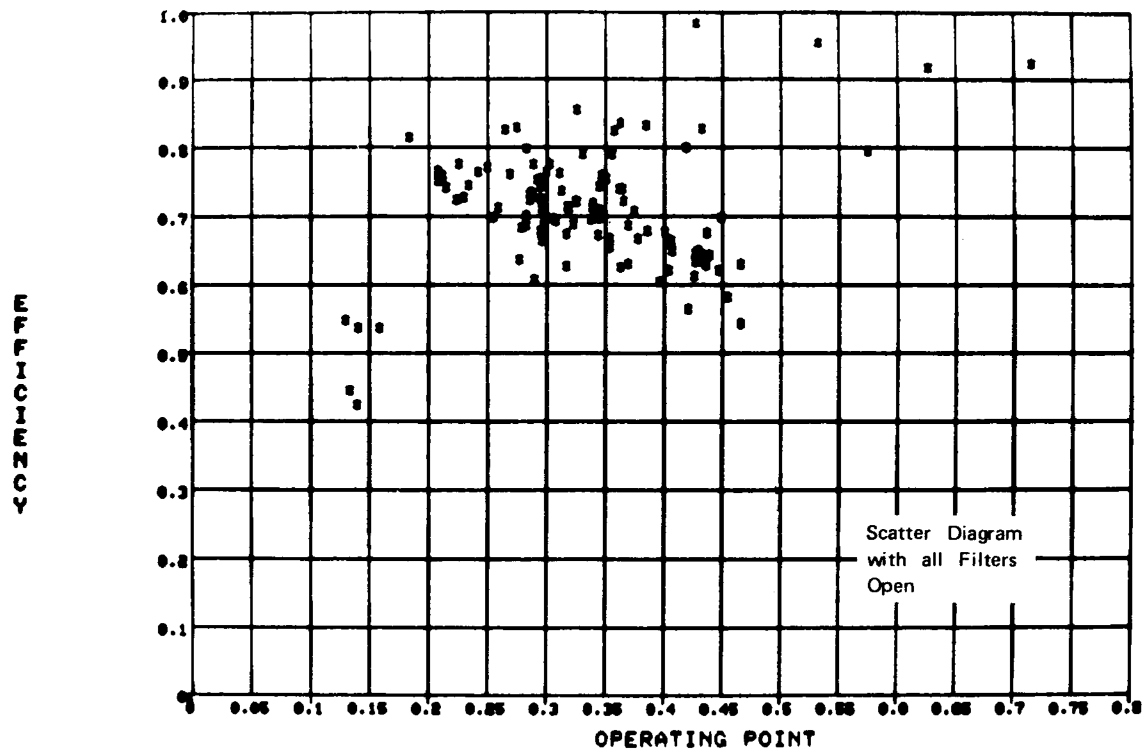

Figure 2. Scatter in Data Points for Aluminum Absorber Copper Tube Collector

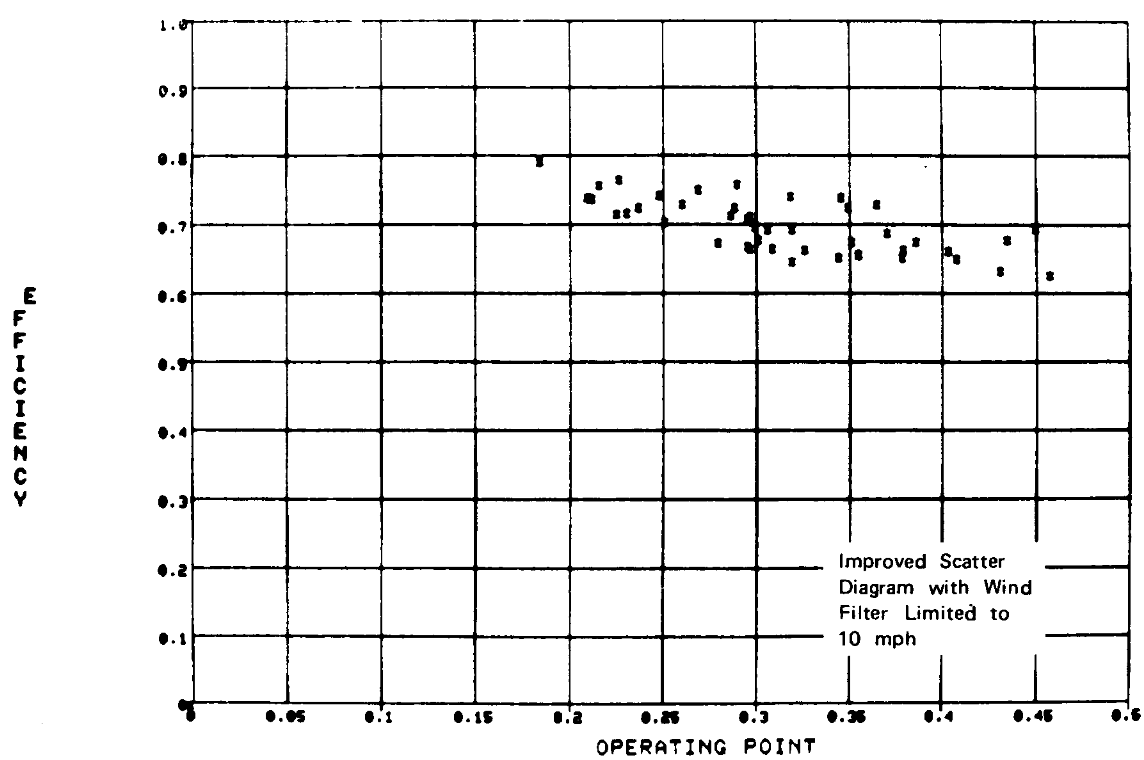

Figure 3. Aluminum Absorber Copper Tube Collector

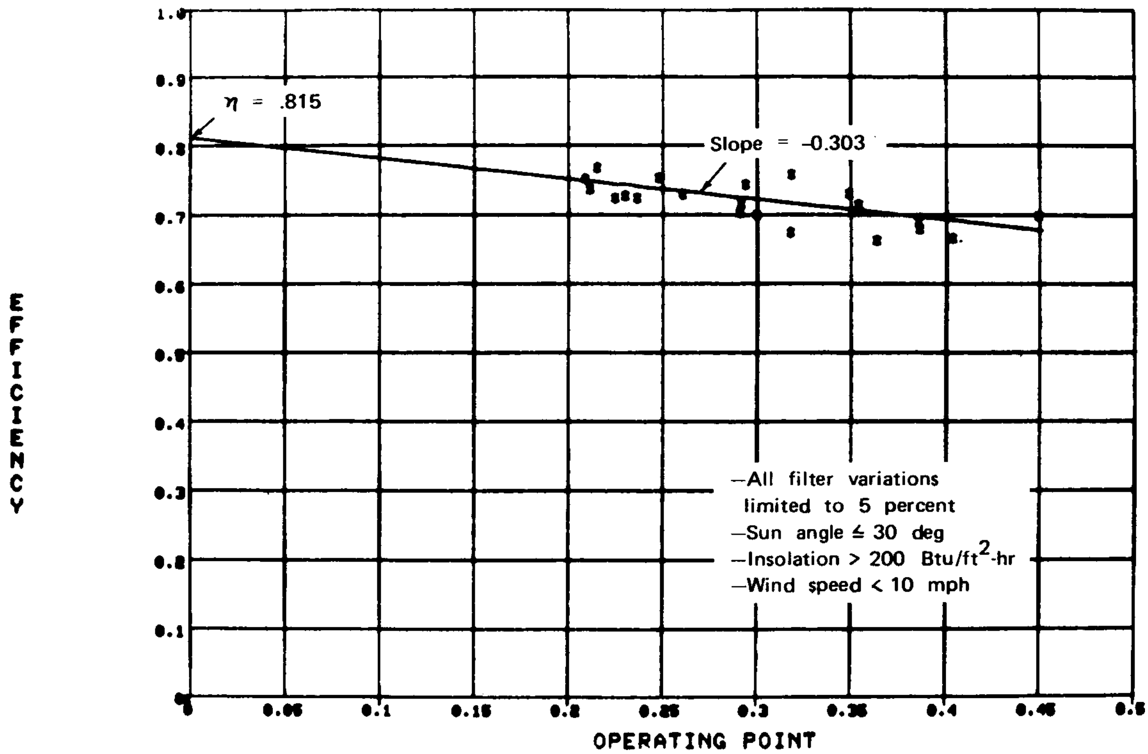

Figure 4. Aluminum Absorber Copper Tube Collector

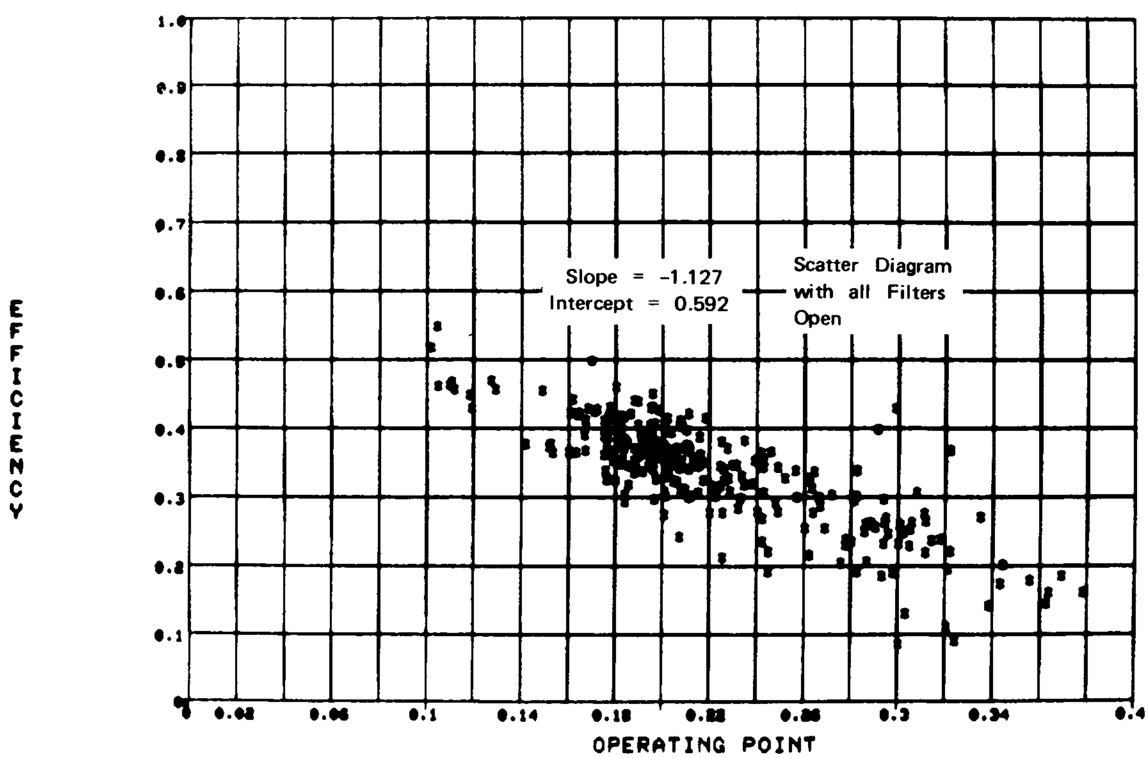

Figure 5. Aluminum Absorber Steel Tube Lexan Glazed Collector

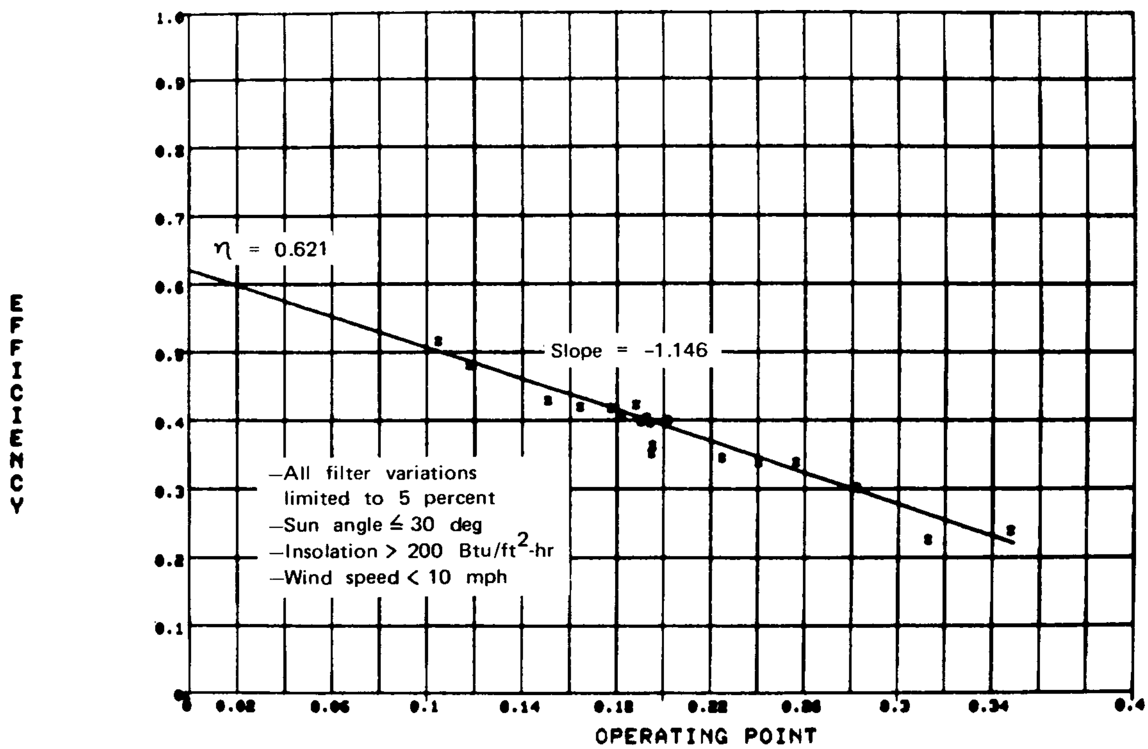

Figure 6. Aluminum Absorber Steel Tube Lexan Glazed Collector

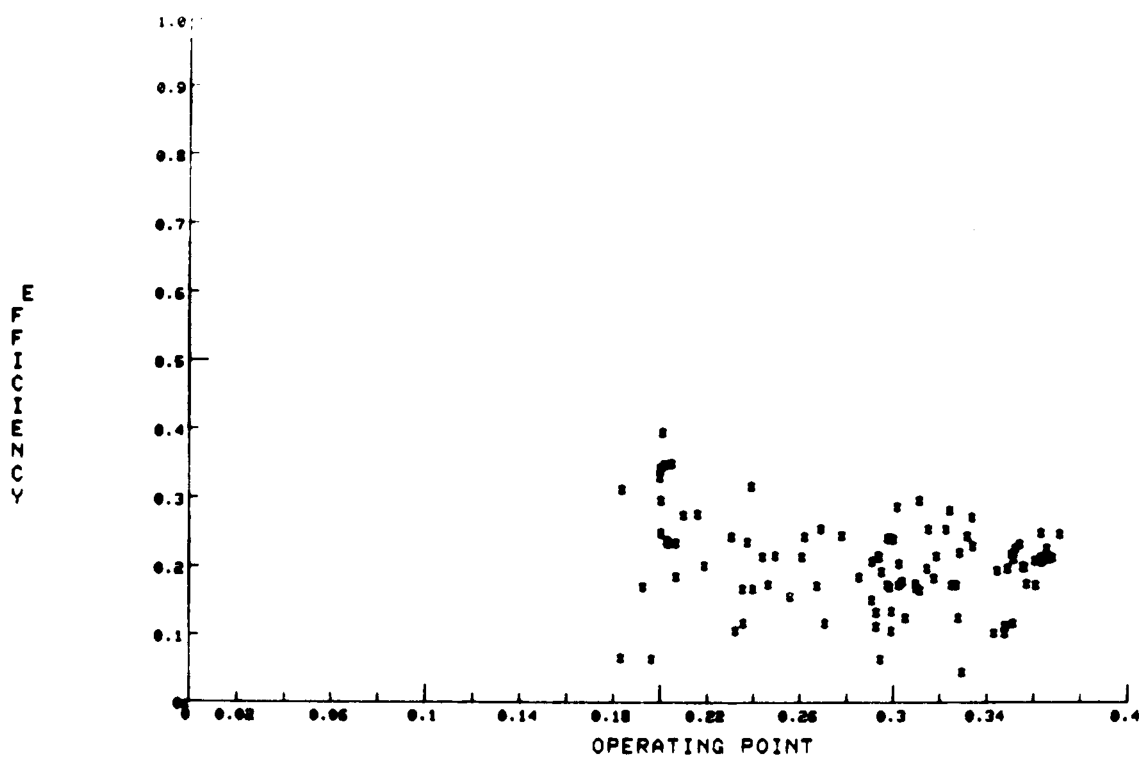

Figure 7. Fresnel Lens Type Concentrator Final Scatter

Figure 7 is the final scatter diagram for an array of Fresnel lens tracking concentrating collectors. It was not possible to reduce the point scatter beyond that shown by using standard filters. In these situations, the collector analysis tool may be used to diagnose the probable causes of non-convergence by iterative selection of filter settings. This particular array was found to be primarily influenced by wind velocity, which, it is postulated, may introduce tracking error or higher losses via manifold heat losses.

CONCLUSIONS

The abundance of raw data available from solar energy demonstration systems permits reference of field performance to the HWB equation. The technique presented in this paper allows for reduction of scattered operating points to a set consistent with the requirements of ASHRAE 93-77. The HWB model thus obtained provides engineers, designers, architects, contractors, and other interested personnel with a model representative of the design's performance, which may then be incorporated into future designs and cost trade analyses. The HWB model obtained from field measurements may also be compared to the predicted performance or controlled test performance data available for collector components. This comparison then allows a more accurate estimation of collector area required to satisfy design loads, ultimately minimizing the cost of solar energy systems.

The technique also provides information as to the impact of environmental conditions on the performance of collector arrays. Sensitivity to wind is of particular importance. Used as an analytical tool, the filters may quantify the local environment; as, for example, in the creation of a site specific wind rose.

The technique has been proven effective. Future papers will include detailed collector array performance analyses, transient source identification and sensitivity to environmental effects for specific collector types.

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