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An Analysis of the Influence of Geography and Weather on Parabolic Trough Solar Collector Design

MASTER

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AN ANALYSIS OF THE INFLUENCE OF GEOGRAPHY AND WEATHER ON PARABOLIC TROUGH SOLAR COLLECTOR DESIGN

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ABSTRACT

The potential performance of single-axis tracking parabolic trough solar collectors as a function of optical energy distribution and receiver size has been calculated for eleven sites using typical meteorological year input data. A simulation based on the SOLTES code was developed which includes the three-dimensional features of a parabolic trough and calculates the thermooptical tradeoffs. The capability of the thermooptical model has been confirmed by the comparison of calculated results with the experimental results from an all-day test of a parabolic trough.

The results from this eleven-site analysis indicate a potential performance superiority of a north-south horizontal axis trough and, in addition, a high quality (optical error, $\sigma_{system} \leq 0.007$ radian) collector should be of the same geometric design for all of the sites investigated and probably for all regions of the country.

ACKNOWLEDGMENT

Figures 3 and 4 supplied by courtesy of B. D. Hansche (Organization 1552).

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AN ANALYSIS OF THE INFLUENCE OF GEOGRAPHY AND WEATHER ON PARABOLIC TROUGH SOLAR COLLECTOR DESIGN

Introduction

The purpose of the analysis described in this report is to determine whether a single-axis tracking parabolic trough solar collector could have a common optimum design for use in all regions of the United States. This determination has an impact upon mass production of troughs since different geometric configurations might be optimum for different regions of the United States and could result in multiple production lines and controlled distribution. Neither is necessarily compatible with the desired cost reductions that could result from large volume production.

Early studies conducted by Treadwell[1] used arbitrary clear day solar and weather input data for the thermooptical analysis of a parabolic trough under normal incidence. These studies resulted in the selection of a 90-deg rim angle, 6.56-ft-aperture collector, and a 1-in receiver outer diameter as an optimum design based upon the assumption that system errors of 7.7 mrad were achievable. The earlier studies did not completely account for performance changes as a function of solar angles of incidence; neither did they consider mechanical deformation of the receiver tube as a function of the tracking angle. Geography and weather were not a factor in these earlier studies.

Because of the variability of weather at various geographical locations, it was necessary to develop a weather standard in order to make logical, reasonable-to-expect performance calculations. This standard was developed at Sandia Laboratories for 26 sites and entitled the Typical Meteorological Year (TMY)[2].

After the creation of the TMY it became possible, on the basis of long-term weather patterns, to calculate the expected annual performance of parabolic troughs. This calculation used a reasonable data base for input. By use of the TMY and a more refined thermooptical code which contained approximations for end losses and angle of incidence effects, an analysis of a single geometric trough configuration operating at low temperatures[3] was conducted to determine the annual performance at the 26 sites throughout the country. The results of this analysis allowed some insight to be developed on which sites might be used for additional comparisons when the code was refined further.

The thermooptical code has been further modified to account for the three-dimensional nature of a parabolic trough and now accounts for two-dimensional end effects, angle of incidence, mechanical deformation, and system optical energy distributions. This code has been used for initial parametric studies to determine the performance of various trough designs. These studies were undertaken in an effort to establish the performance sensitivity of various geometric designs to weather and geography, and to determine whether the previously selected optimum geometric design should be changed.

Discussion

Code Development

The thermooptical collector analysis routines were developed to be compatible with the SOLTES[4] driver program, weather information routine, loop control information, and the fluids coefficient data. The model for this and previous analyses consisted of a collector and a load component in a closed loop (Figure 1). The function of the load component is to provide the chosen heat transfer liquid at a constant input temperature and mass flow rate to the collector. A cumulative sum of the energy added to the heat transfer fluid during its passage through the collector is retained in an integrating subroutine in SOLTES. The collector was shut off if its outlet temperature was equal to or less than the input temperature (or if the sun had a negative elevation angle). Thermal inertia was not considered* because of the comparative nature of this analysis for the collectors only.

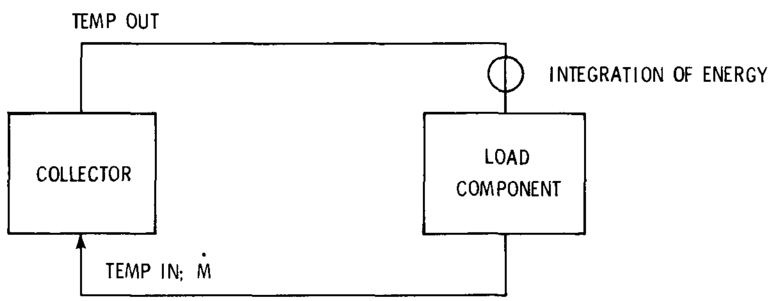

Figure 1. Model of Collector and Load Component

An optical energy deposition subroutine, EDEP,** was incorporated into the collector routine. This subroutine statistically calculates reasonably precise optical energy input onto the receiver as a function of the receiver location and the circumferential position around the receiver. The subroutine contains end effects and two-dimensional angle of incidence effects. The captured energy is averaged over the receiver area for all thermal calculations.

The thermal portion of the collector routine calculates the thermal gains and losses over the collector length assuming that the temperature changes linearly along the length. With the presently developed routine, the only alternative is to calculate losses with atmospheric pressure in the annulus between the receiver and its glass cylindrical cover. The displacement of the receiver from focus as a result of its weight and the tracking angle of the collector is calculated and the receiver is then divided into a series of segments, each of which is rotated until it is

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*This is not to imply that thermal inertia is not important. Flow control studies are being conducted at Sandia to determine startup and shutdown considerations as well as equipment for flow and temperature control of a complete system.

**A Sandia report on EDEP is projected.

parallel to the focal line as shown in Figure 2. The optical energy input is then calculated for these segments.

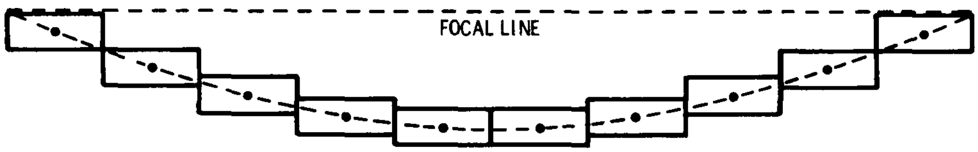


Figure 2. Receiver Segment Rotation

Although the SOLTES routines are designed to be run on the CDC 6600 computer, the calls to the EDEP subroutine are time consuming so that reading and executing the 8760 hourly inputs from a TMY site for an annual performance calculation take a long time. Various solar symmetry conditions were used to decrease the code's running time. The symmetry of the sun's position versus time of year permitted a reduction in the number of calls to the EDEP subroutine; for example, all of the solar angle calculations and dimensionless energy deposition calculations for days 171 and 173 are identical because they are symmetrical with respect to day 172, the day of maximum solar declination. The number of calls was reduced by approximately a factor of four because of the day-to-day and the morning-to-afternoon angle symmetry. Because of the calculational construction for this technique, the permissible latitudes for this code are 49°N or less so that sunrise and sunset times are less than 8 hours from solar noon. Since this latitude encompasses the contiguous United States, it is satisfactory for all TMY sites.

The changes to the routine permit an annual calculation to be completed in approximately 1 hour of central processor time so it can be understood why this study did not examine all 26 TMY sites. Techniques to decrease the running time by an order of magnitude are available but have not yet been incorporated into the code.

Code Confirmation

More confidence in the accuracy of the annual performance predictions is possible since the simulation model has been verified experimentally. Valid experimental data exist for an advanced design parabolic trough[5] that has been tested in the Collector Module Test Facility at Sandia Laboratories. Five hours of test data with an almost constant input temperature have been used to determine how accurately the model can predict the actual experimental performance of the optically characterized advanced trough. The experimental apparatus has been described in other reports.[6 7 8] The five hours of data were examined and then separated into 5-minute averages. The 60 data points at 5-minute intervals were used as data input for the collector routine so that calculated efficiencies could be compared with experimental efficiencies obtained under nonnormal angles of incidence.

The experimental trough has a nonnormally distributed slope error. The cause and effect of this nonnormal distribution are shown in Figures 3 and 4, respectively.

The shape of the surface and its displacement from the theoretical parabolic position are shown in Figure 3. The linear appearance of the surface's distortion along its long axis is suggestive of a "chorded" surface. The theoretical image caused by this surface is shown in Figure 4 on an unfolded imaginary receiver in terms of numbers of suns. These striations of energy are observed on the experimental collector receiver tube.

The result of this nonnormally distributed reflection of energy is that more optical energy misses the experimental collector receiver tube than would be calculated for a surface with a normal distribution of slope errors. The use of the nonnormal distribution (referred to as the bias function) as an input to the computer model results in a lower calculated efficiency. The normal distribution calculation and the bias function calculations are shown in Figure 5 for comparison with the experimental results.

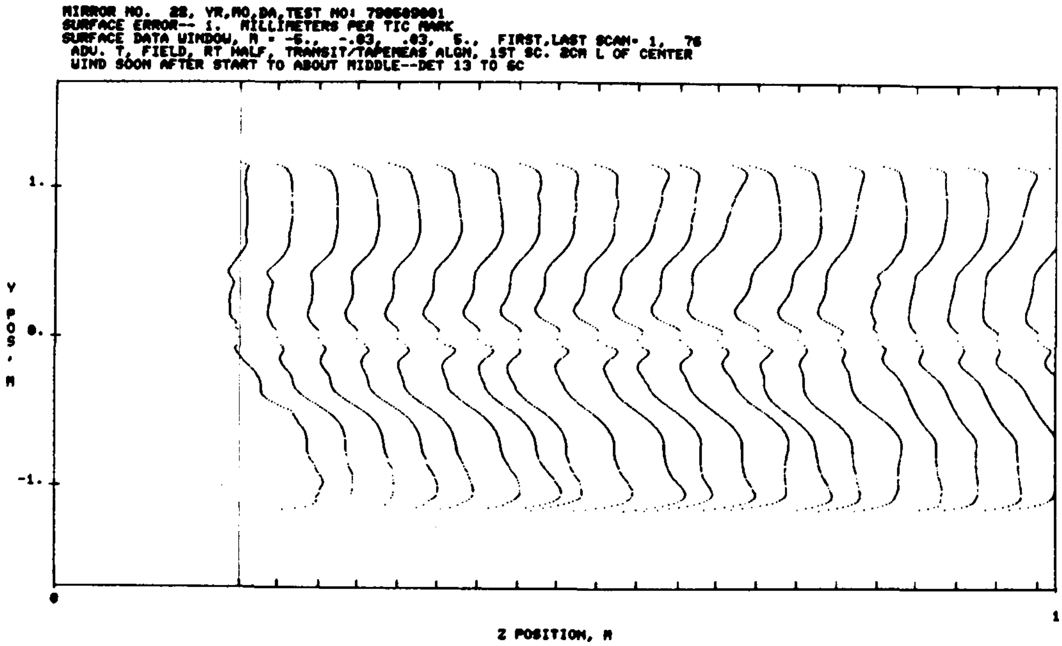


Figure 3. Displacement of Surface from Theoretical Parabolic Position

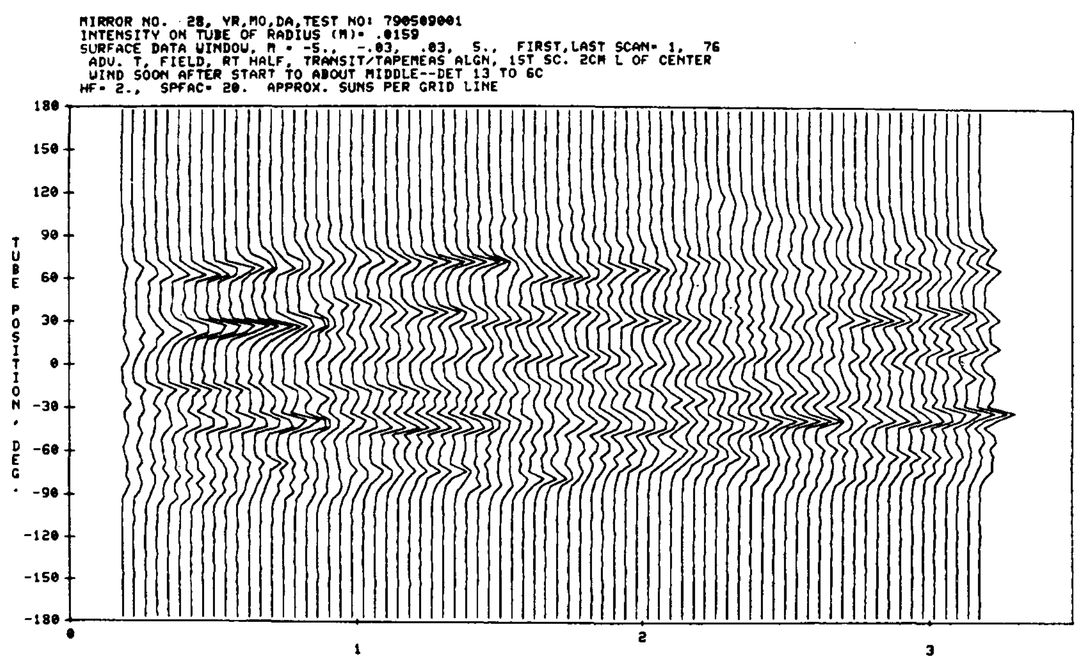
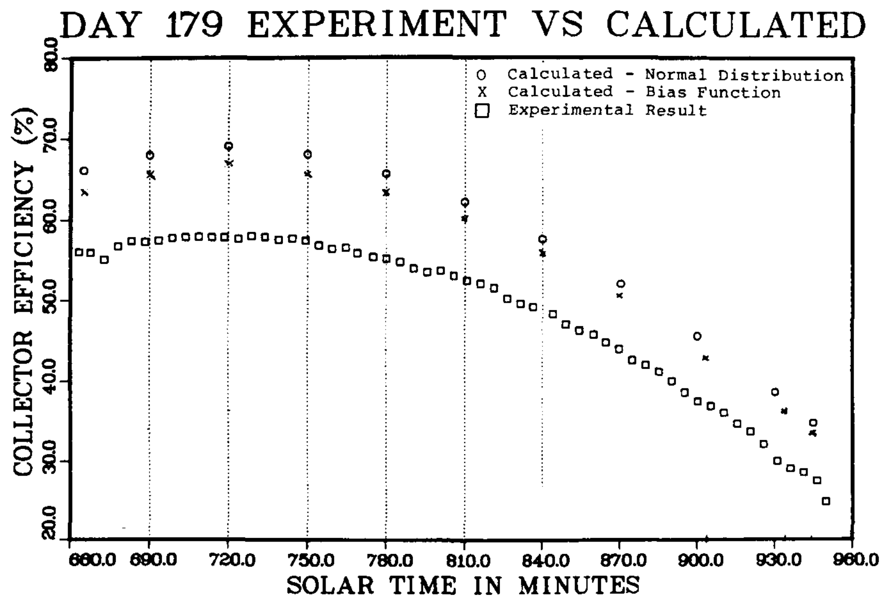


Figure 4. Energy Intensity Variations on Imaginary Unfolded Receiver Tube



Basis for Calculations

Collector Orientation	= EW
Reflector Width	= 2.0 m
Reflector Length	= 12.2 m
Receiver Length	= 12.2 m
Focal Length	= 0.489 m
Glass Diameter	= 0.06 m
Receiver Diameter	= 0.0318 m
Specular Reflectance	= 0.95
Coating Absorptance	= 0.95 (normal, otherwise polynomial fit)
Coating $\text{Emittance}_{500°F}$	= 0.2
Rim Angle	= 92 deg
Standard Deviation of Optical Errors	= 0.012 radians; Non-Normally Distributed Errors (Bias)

Measured insolation, wind velocity, ambient temperature, flow rate and temperature for input (5 min averages)

Figure 5. Calculated versus Experimental Results, All-Day Test

The differences between the calculated and experimental results can be explained by a number of factors. Since the experimental collector (characterized by the parameters listed in Figure 5) has a 2/3-ft reflector gap at the center support pylon, approximately 1 ft of non-glassed receiver length, and receiver supports which occlude the receiver, the experimental results are expected to be lower than the calculated results. An estimate of these effects is approximately 3 points of efficiency. The reflective surface covers only about 99% of the aperture of the experimental collector which is about a 1-point effect.

If an estimate of the experimental instrumentation error band is ±3%, it is believed that the difference shown between the calculated and experimental results can be explained. Therefore, it appears reasonable to use the code calculations for predictions of expected annual performance and certainly for comparisons of various geometric configurations. Efforts to resolve the differences more precisely will continue.

Collector Configuration

The collector configuration selected for the basic analysis is a 6.56-ft-wide aperture trough with a 90-deg rim angle and a length of 103 ft to minimize end effects. Preliminary parametric studies resulted in the selection of optimum values for a number of variables. The Reynolds number for water* flow was established at 120,000 to assure turbulent flow and good heat transfer. The collector input temperature was 500°F. The energy deposition was calculated at 8-deg intervals around the circumference of the receiver which was presumed to permit an adequately defined integral; a smaller angular interval could have resulted in slightly greater precision but would have had greatly increased running time. A similar tradeoff was used to establish the number of receiver segments at 2 (length ≃5 ft); more segments would have resulted in greater precision but also in more use of computer time.

An airgap of 0.287 in (7.3 mm) was established between the nonantireflection coated glass and the receiver as the optimum gap for all receiver diameters for maximum energy gain on an annual basis. The total hemispherical emittance of the black chrome was established at 0.2, a value currently representative at 572°F after the use of experimental

*Water was used for convenience. The more typical heat transfer oils could have been used without significant changes in results.

production plating baths. (Increasing the emittance to 0.3 results in only a 4.3% decrease in annual performance using the glass total hemispherical emittance of 0.9.)

Results

The results of the calculations of the TMY annual performance as a function of the receiver diameter and the total system energy distribution are shown graphically in Figures 6 through 16. It should be noted that a goal of the trough development program at Sandia is a system error of 7 mrad. Several additional calculations are shown on the Albuquerque, NM and Great Falls, MT charts, specifically the performance of a 72-deg rim angle trough and the results of varying the chosen reflectance value by +0.05 unit for different system energy distributions.

With a system energy distribution, σ, of 0.007 radian, the performance enhancement obtained by orienting the trough in a north/south horizontal direction as compared to an east-west direction is calculated in Table 1.

TABLE 1

Annual Performance Enhancement Using TMY
NS Horizontal Versus EW
(σ_{sys} = 0.007 radian)

Location	% Performance Enhancement (NS/EW (%) - 100%)
Albuquerque, NM	15
Caribou, ME	7
Dodge City, KS	14
El Paso, TX	18
Ely, NV	21
Fort Worth, TX	16
Fresno, CA	23
Great Falls, MT	9
Lake Charles, LA	16
Phoenix, AZ	16
Santa Maria, CA	12

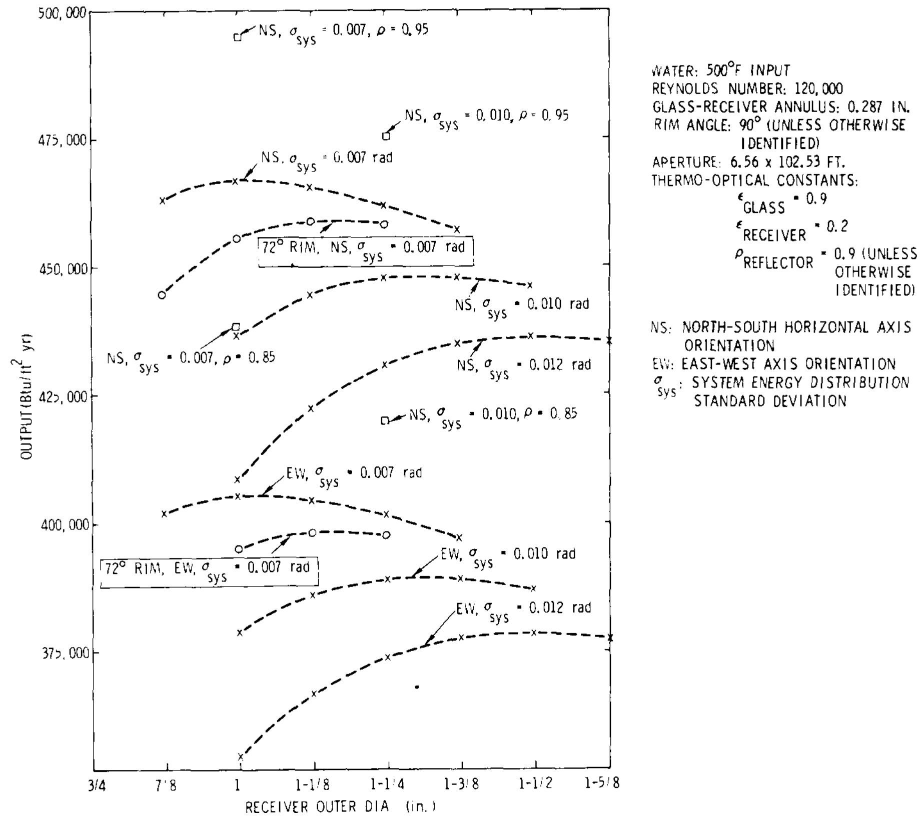


Figure 6. Parabolic Trough TMY Annual Performance, Albuquerque, NM

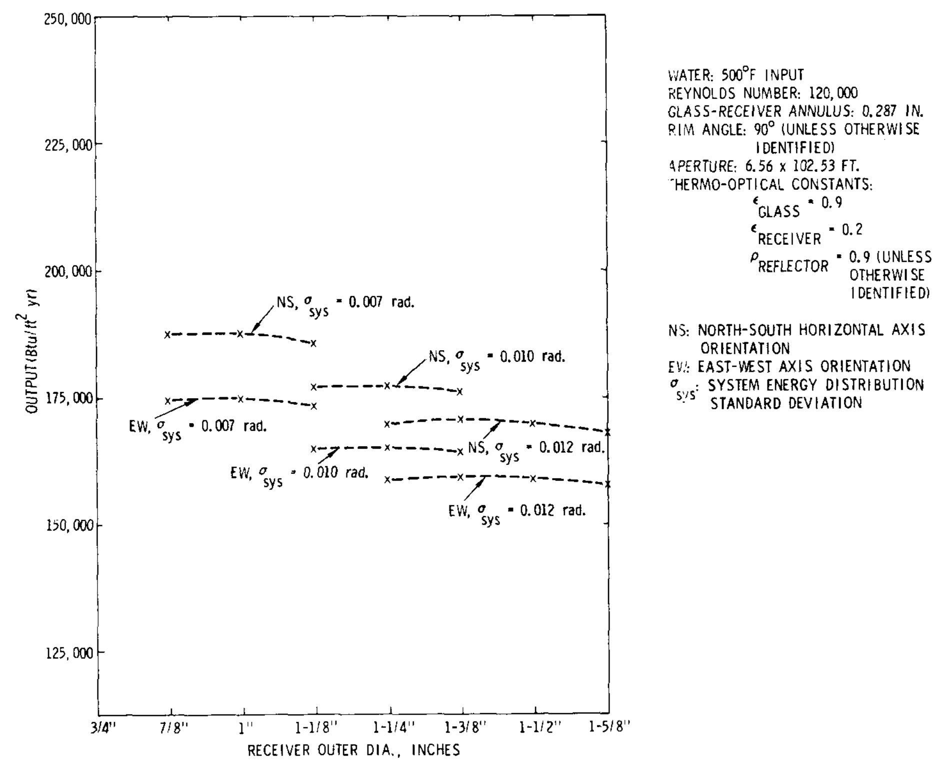


Figure 7. Parabolic Trough TMY Annual Performance, Caribou, ME

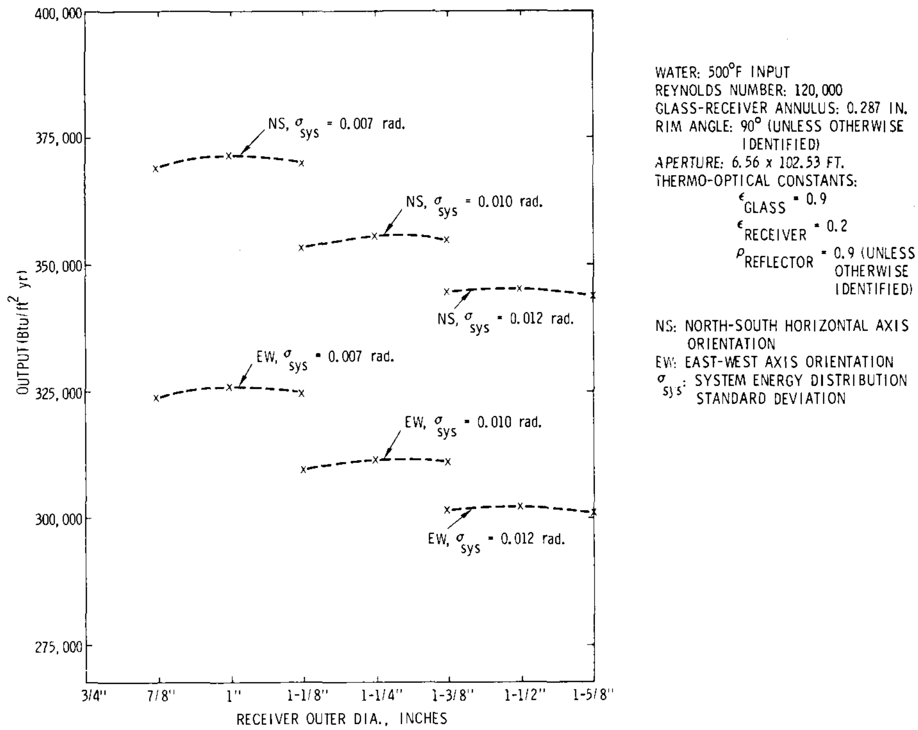


Figure 8. Parabolic Trough TMY Annual Performance, Dodge City, KA

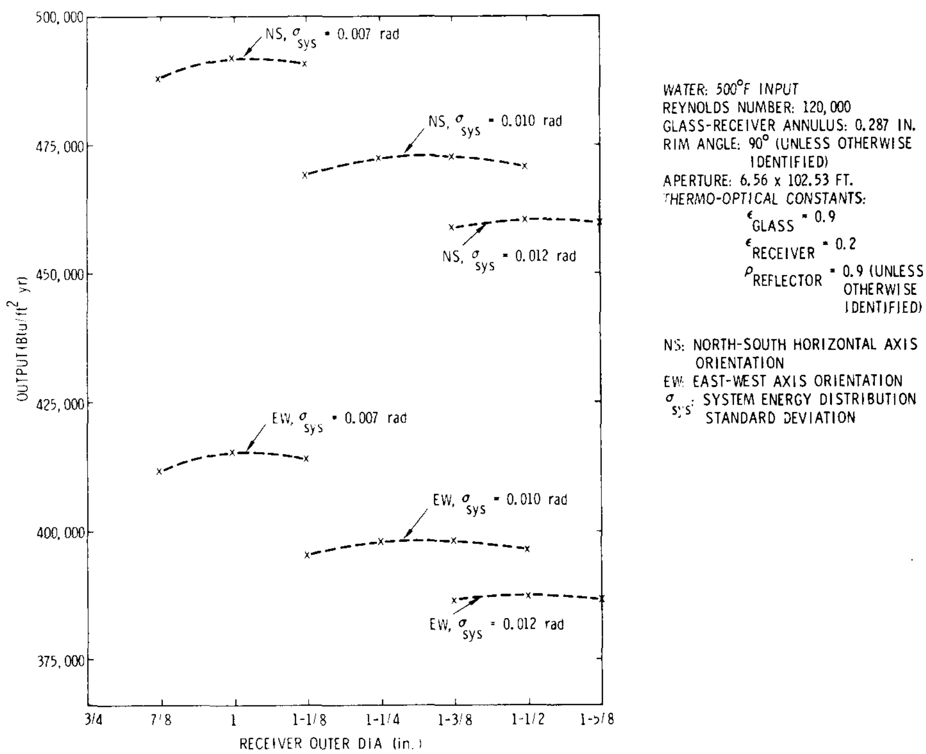


Figure 9. Parabolic Trough TMY Annual Performance, El Paso, TX

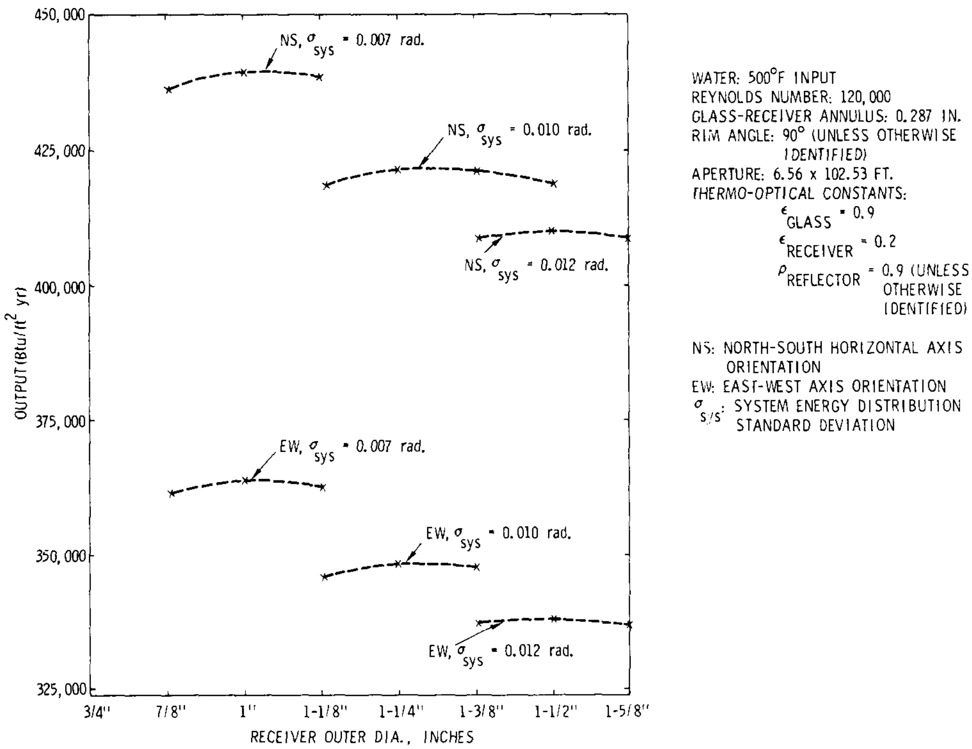


Figure 10. Parabolic Trough TMY Annual Performance, Ely, NV

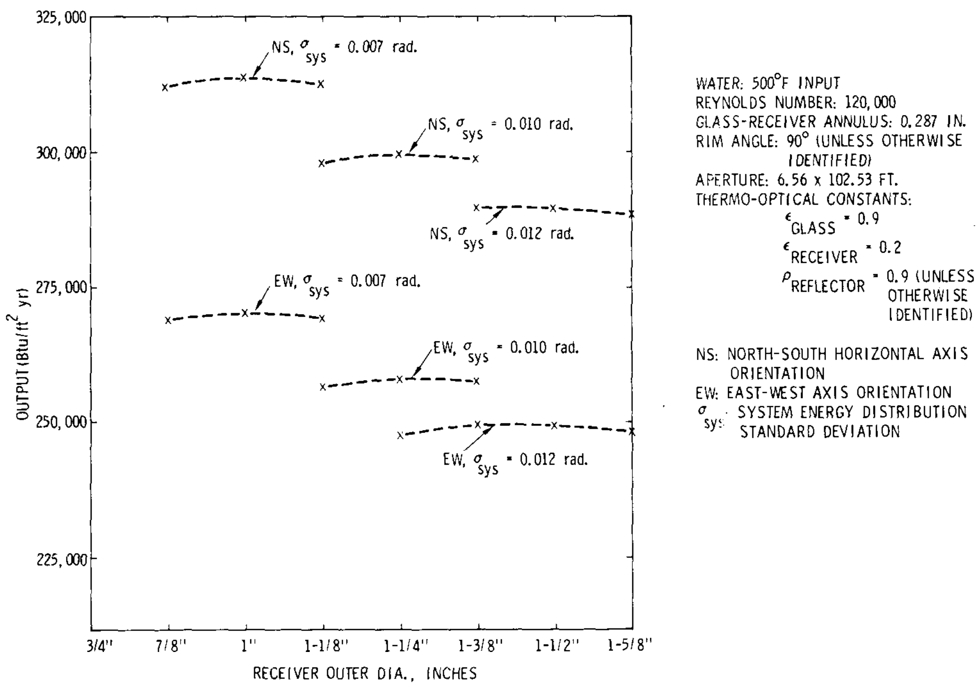


Figure 11. Parabolic Trough TMY Annual Performance, Fort Worth, TX

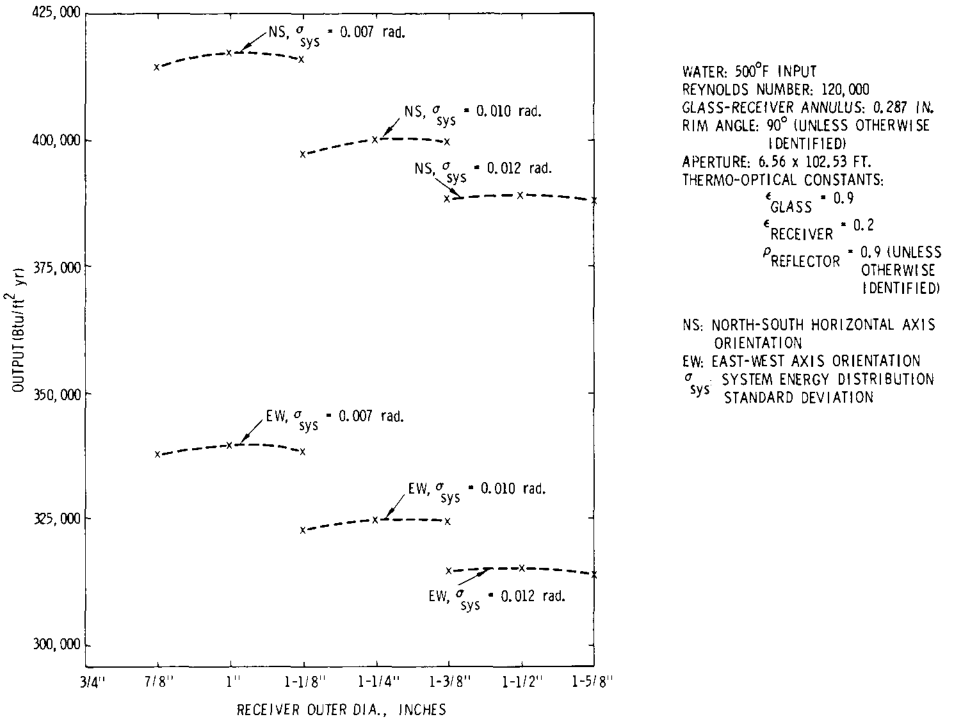


Figure 12. Parabolic Trough TMY Annual Performance, Fresno, CA

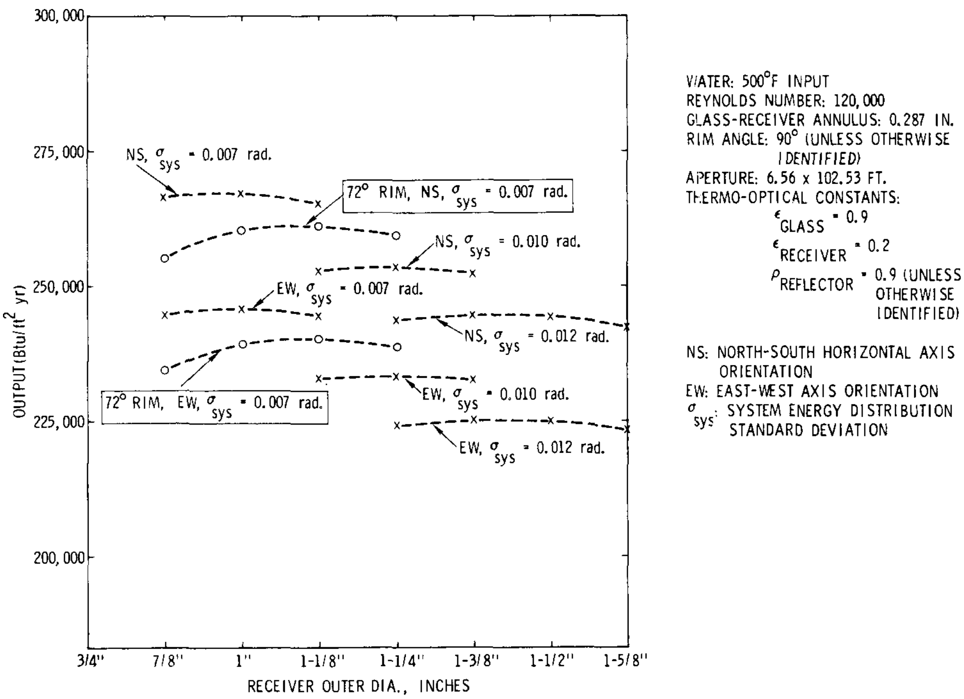


Figure 13. Parabolic Trough TMY Annual Performance, Great Falls, MT

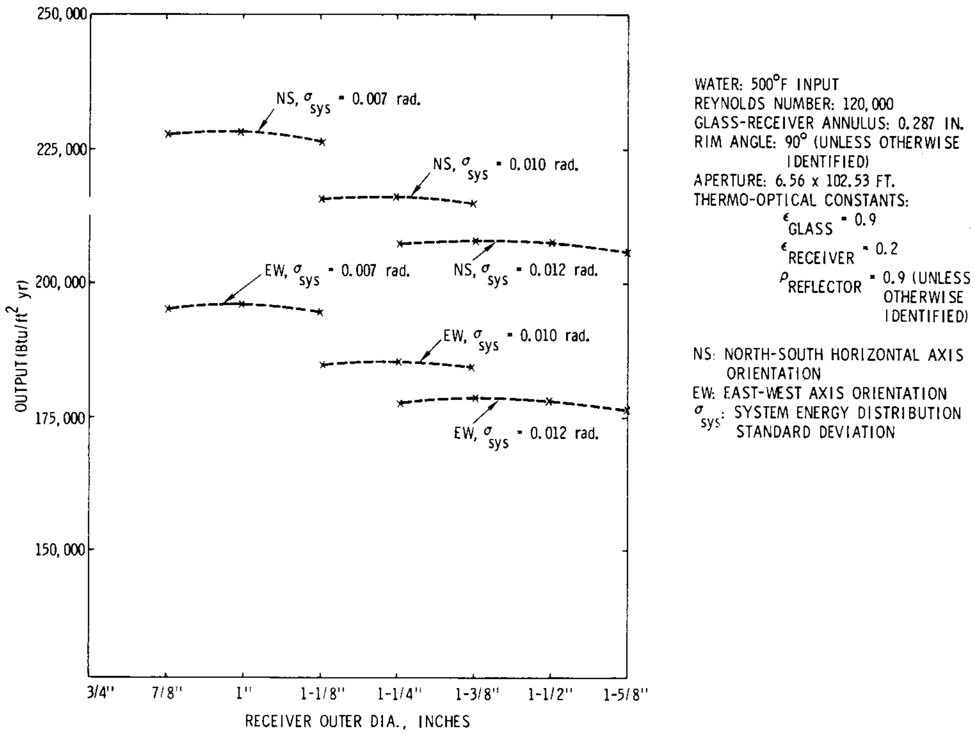


Figure 14. Parabolic Trough TMY Annual Performance, Lake Charles, LA

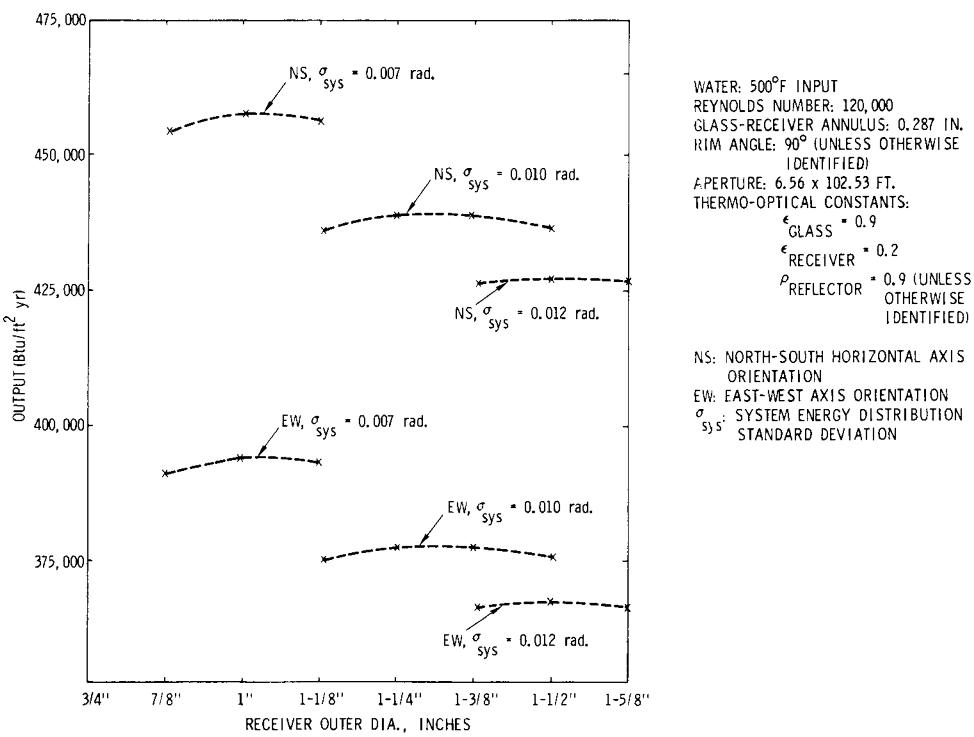


Figure 15. Parabolic Trough TMY Annual Performance, Phoenix, AZ

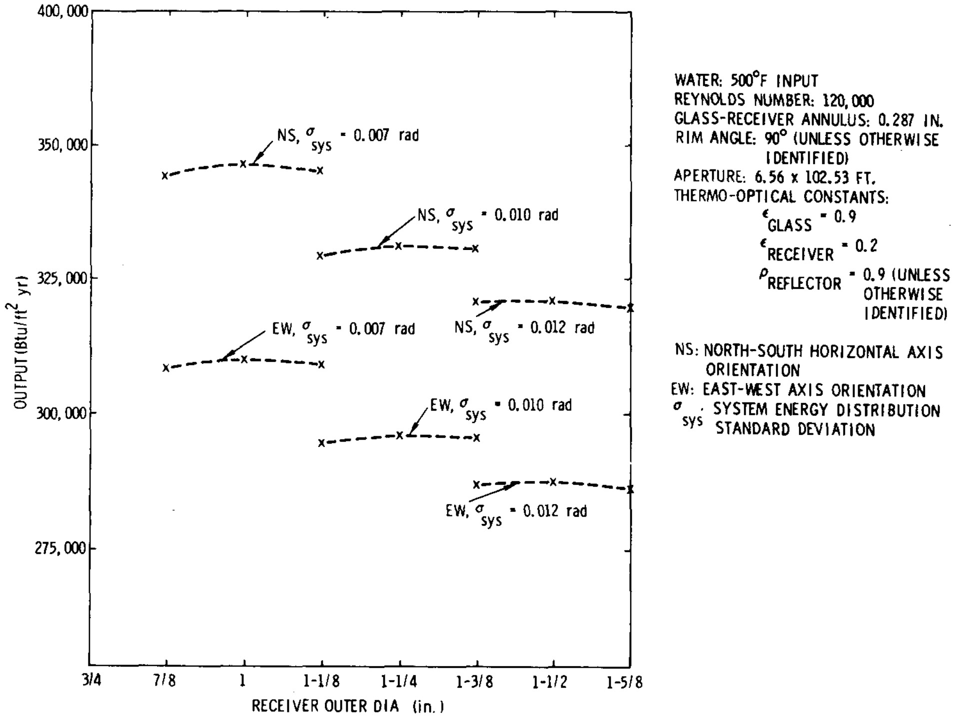


Figure 16. Parabolic Trough TMY Annual Performance, Santa Maria, CA

It can be observed that there are some weather patterns in Ely, NV and Fresno, CA which favor a north-south orientation. For example, the central valley of California has significant cloud cover in the winter which detracts from the relative performance of the east-west orientation. The influence of latitude can be deduced to some extent, i.e., lower latitudes favor north-south orientation because of more favorable incidence angles.

Figures 17 and 18 portray the equal performance contours of north-south and east-west systems with an energy distribution of 0.007 radian. The computer programs of Akima[9] and Dayhoff[10] were used to obtain data for these plots.

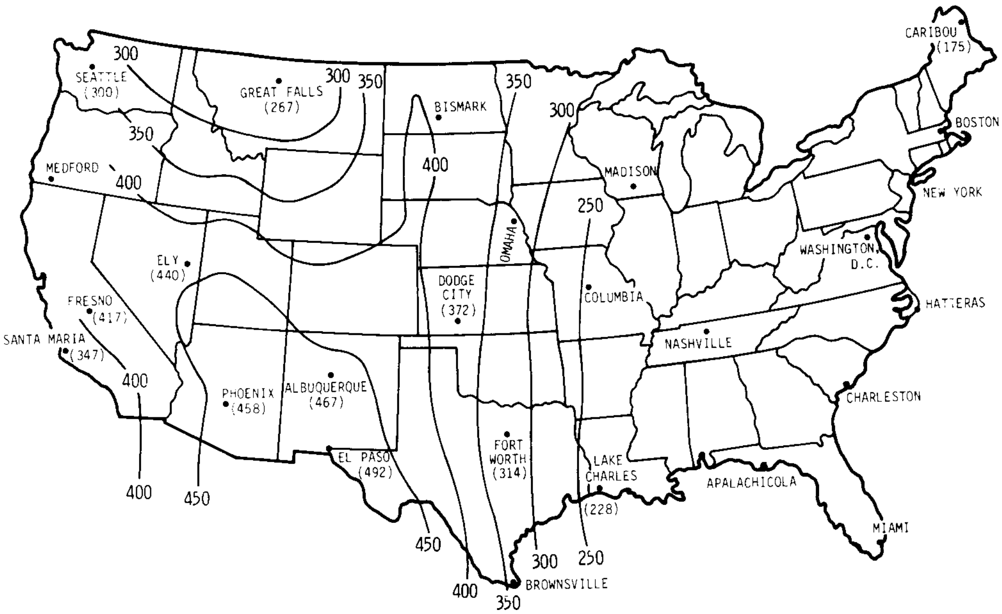


Figure 17. Annual Energy Output at 500° F Inlet Temperature ($KBTU/FT^2YR$) and Approximate Contours, North-South Horizontal Parabolic Trough Collector (TMY)

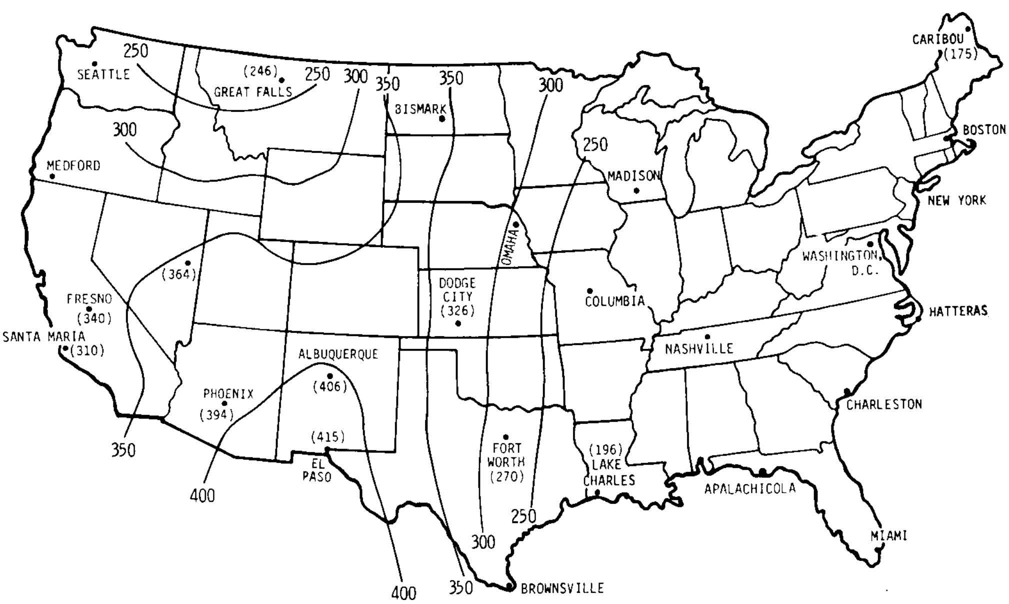


Figure 18. Annual Energy Output at 500° F Inlet Temperature ($KBTU/FT^2YR$) and Approximate Contours, East-West Parabolic Trough Collector (TMY)

Conclusions

Within the established receiver tube size intervals chosen for the comparison and an energy distribution of 0.007 radian, the optimum outside diameter receiver tube size for all investigated locations is 1-in. Since the investigated sites include low and high latitudes and eastern and western longitudes, the tentative conclusion is that a high quality (σ_s = 0.007 radian) parabolic trough geometric configuration design can be common for the contiguous United States for either north-south, or east-west orientation.

The optimum design for lower quality ($\sigma_s > 0.007$ radian) collectors cannot be clearly ascertained. The thermooptical tradeoffs indicate essentially equal performance for ranges of receiver sizes as a function of geographic location. The optimum receiver size range for Caribou, ME, is different than the range for Albuquerque, NM for example. One redeeming feature is that, regardless of which receiver diameter is chosen within a broad range of sizes, the annual performance is not significantly different for a given energy distribution.

As can be observed from the Albuquerque results, any tentative selection of receiver size should err on the high side. A degradation in the optical intercept factor is more damaging to performance than increases in the thermal loss factor.

The 72-deg rim angle and the reflectance change calculations shown on the Albuquerque and Great Falls charts were included to confirm that the code can discriminate for changes in these parameters. For a given aperture size, a 72-deg rim angle collector has a lower performance potential because its focal length is longer for the same aperture width, which leads to a larger optimum receiver size.

An unshadowed north-south horizontal collector has a greater annual performance potential than an east-west oriented trough. Not only are there geographical considerations which force consideration of north-south orientation as the primary choice but prevailing weather patterns tend to enhance the performance differential.*

Although this analysis did not include all 26 TMY sites, the insights derived from this and previous studies suggest that a 6.56-ft-aperture trough with a 1-in-diameter receiver could serve as an initial configuration for volume production consideration.

This effort has indicated that a more thorough examination of these factors now incorporated into the newly modified code reveals them to have a second-order effect on comparisons for properly designed collectors. The geometric configuration previously selected for consideration is essentially unchanged. This suggests simpler codes that model the first-order factors can be fruitfully used for performance calculations. The newly modified code is appropriate to use for design tradeoffs.

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*Geography and weather patterns are not the sole determinants of the orientation choice. Shadowing, energy storage, load matching, and site configuration are among the other determinants.

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