AN ANALYSIS OF MIRROR ACCURACY REQUIREMENTS FOR SOLAR POWER PLANTS [1].

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THE MIRROR ACCURACY REQUIRED TO COLLECT SOLAR ENERGY IN A SUBSTANTIALLY BLACK CAVITY AT VARIOUS TEMPERATURE LEVELS IS INVESTIGATED. WITH THE ACCURACY DEFINED IN TERMS OF THE STANDARD DEVIATION σ, OF THE ANGLE BETWEEN PLANES TANGENT TO THE ACTUAL AND THE IDEAL PARABOLIC MIRROR AT A MULTIPLICITY OF POINTS, THE FOLLOWING RESULTS WERE FOUND: A MIRROR INCLUDED ANGLE OF 120° MINIMIZES THE EFFECT OF MIRROR INACCURACIES, A VALUE OF σ IN THE NEIGHBORHOOD OF 1.0° IS REQUIRED TO COLLECT SOLAR ENERGY FOR MEDIUM TEMPERATURE RANKINE POWER PLANTS, AND VALUES OF σ WELL BELOW 1/4° ARE REQUIRED TO COLLECT ENERGY FOR HIGH TEMPERATURE THERMIONIC SYSTEMS.

INTRODUCTION

DURING THE PAST FEW YEARS, A NUMBER OF PAPERS HAVE BEEN PRESENTED WHICH SET FORTH METHODS FOR DETERMINING THE EFFICIENCY OF COLLECTION OF SOLAR ENERGY CONCENTRATED BY A PERFECT PARABOLIC MIRROR. THE FINITE ANGLE OF THE SUN DISK AND THE VARIATION IN THE LENGTH AND ANGLE OF APPROACH OF THE REFLECTED RAY ARE THE VARIABLES WHICH DETERMINE THE SPREAD OF THE SOLAR FLUX ON A HYPOTHETICAL TARGET SITUATED AT THE FOCUS OF THE MIRROR IN A PLANE PERPENDICULAR TO THE MIRROR AXIS. IN PRACTICAL MIRRORS CONTEMPLATED FOR SOLAR ENGINE SYSTEMS, THE SPREAD DUE TO THESE FACTORS IS SMALL COMPARED WITH THAT DUE TO ERRORS IN THE GEOMETRY OF THE MIRROR SURFACE ITSELF. THE FACT THAT THE MIRRORS WILL BE EXTENSIBLE, ULTRA-LIGHT, MADE OF PLASTIC OR STRIPS OF ALUMINUM, WITH LARGE INHERENT FLEXIBILITY MAKES THIS INTUITIVELY APPARENT. THE FEW TESTS ALREADY ACCOMPLISHED ON NON-INTEGRAL MIRRORS HAVE SUBSTANTIATED THIS CONCLUSION.

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1. PRESENTED AT THE ARS SEMI-ANNUAL MEETING, AMBASSADOR HOTEL, LOS ANGELES, CALIFORNIA, MAY 9-12, 1960.

The analysis presented in this paper develops the relationship between the geometric error of the mirror surface and the efficiency of collection of solar energy. The assumption is made that the inaccuracies have a normal distribution with a deviation σ. The collection efficiency is determined as a function of the collector temperature (which is a measure of the flux re-radiated from the target) and the normal deviation of the error in the mirror surface (which is a measure of the flux spread on the target.) But first an analysis is presented which describes where on the target, a ray with a given error angle will fall. An interesting by-product of this analysis is that it also shows the optimum included angle (or focal length to diameter ratio) for a parabolic reflector with geometric inaccuracies.

The first section of the paper concerns itself with this problem. The second section makes use of these results to obtain collection efficiencies for a variety of interesting cases.

FOCAL PLANE DISTRIBUTION OF RAYS REFLECTED FROM POINTS ON A MIRROR WITH GEOMETRIC ERRORS.

Before persuing this analysis, it should be emphasized that the mirror error with which we deal here is not a dimensional error, but rather an error in the angle of the plane tangent (or normal) to the mirror at any point. The tangent plane is defined by two angles as indicated in Figure 1. Thus, δ_1, is the angular error in a plane through the axis, and δ_2 is the error in the plane perpendicular to the axial and tangent planes. The distance ε_1, is the error (linear distance from the ideal focus) due to δ_1, ε_2 the error due to δ_2.

The problem then reduces itself to the determination of ε_1, and ε_2 in terms of the angular errors and the geometry of the unit. For definition of the symbols, refer to Figure 1.

Let the parabolic shape of the mirror be defined

$$Y = \frac{\tan \theta_c}{2 X_c} X^2$$

where θ_c is the tangent angle at the outer diameter, X_c.

Then

$$\varepsilon_1 = \frac{2 \ell \delta_1}{\cos 2\theta}$$

AND $$\cos 2\theta = \frac{b - Y}{\ell}$$

WHERE b IS THE DISTANCE FROM THE FOCUS TO THE MIRROR ALONG THE AXIS,

$$b = Y_0 + \frac{x_0}{\tan 2\theta_0} = x_0 \left[\frac{\tan \theta_c}{2} + \frac{1}{\tan 2\theta_c} \right]$$

$$\ell = \sqrt{X^2 + (b - Y)^2}$$

SUBSTITUTING FOR b, Y, AND ℓ, ONE OBTAINS THE FOLLOWING RESULTS.

$$\frac{\mathcal{E}_1}{x_0\, \delta_1} = f_1 = 2 \frac{\left\{ \left(\frac{X}{X_c}\right)^2 + \left[\frac{\tan\theta_c}{2}\left(1 - \frac{X^2}{X_c^2}\right) + \frac{1}{\tan 2\theta_c} \right]^2 \right\}}{\left[\frac{\tan\theta_c}{2}\left(1 - \frac{X^2}{X_c^2}\right) + \frac{1}{\tan 2\theta_c} \right]}$$

SIMILARLY

$$\frac{\mathcal{E}_2}{x_0\, \delta_2} = f_2 = 2 \left\{ \left(\frac{X}{X_c}\right)^2 + \left[\frac{\tan\theta_c}{2}\left(1 - \frac{X^2}{X_c^2}\right) + \frac{1}{\tan 2\theta_c} \right]^2 \right\}^{\frac{1}{2}}$$

THE LEFT HAND EXPRESSIONS THUS DEFINE THE EFFECT OF AN ANGLE ERROR ON THE POSITION ERROR AT THE FOCUS, AS A FUNCTION OF THE MIRROR INCLUDED ANGLE ($4\theta_c$) AND THE RADIUS. THESE ARE PLOTTED IN FIGURES 2 AND 3. IT SHOULD BE NOTED THAT THE GREATER THIS VALUE, THE LARGER THE POSITION ERROR FOR A GIVEN ANGLE ERROR. IT CAN BE SEEN THAT THE AVERAGE VALUE IS SMALLEST FOR INCLUDED ANGLES BETWEEN 90 AND 120 DEGREES. FIGURE 4 HAS BEEN ADDED TO SHOW THE FUNCTION WEIGHTED WITH RESPECT TO THE RADIUS, SINCE THE AREA OF A GIVEN INCREMENT OF RADIUS INCREASES LINEARLY WITH RADIUS. HERE IS SHOWN EVEN MORE EXPLICITLY THAT AN INCLUDED ANGLE IN THE NEIGHBORHOOD OF 120 DEGREES IS OPTIMUM.

ENERGY DISTRIBUTION ON THE FOCAL PLANE AS A FUNCTION OF MIRROR ERROR.

TO DETERMINE THE EFFECT OF MIRROR ANGULAR ERRORS ON COLLECTION EFFICIENCY, IT CAN BE ASSUMED THAT THE MIRROR NORMAL ANGULAR ERRORS WILL HAVE A NORMAL DISTRIBUTION; THAT IS, THAT THE FREQUENCY CURVE WILL HAVE A DISTRIBUTION AS FOLLOWS:

$$P_1(\delta_1 + \Delta\delta_1) - P_1(\delta_1) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\delta_1}{\sigma}\right)^2\right] \Delta\delta_1$$

$$P_2(\delta_2 + \Delta\delta_2) - P_2(\delta_2) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\delta_2}{\sigma}\right)^2\right] \Delta\delta_2$$

WHERE; σ = THE STANDARD DEVIATION OF THE MIRROR ANGLE. (0.67 PERCENT OF THE AREA HAS A SMALLER ABSOLUTE ERROR ANGLE THAN σ).

δ_1, δ_2 = ARE ANGULAR ERRORS AS PREVIOUSLY DEFINED.

$P(\delta)$ = THE PROPORTION OF AREA HAVING AN ERROR LESS THAN δ.

IN ORDER TO DETERMINE THE EFFECT OF THE ANGULAR ERRORS ON COLLECTION EFFICIENCY, THE δ'S MUST BE WRITTEN IN TERMS OF THE $\mathcal{E}$'S, THE TARGET ERROR, IN SOMEWHAT THE SAME MANNER AS SHOWN IN SECTION II. TO DO THIS A RATHER INVOLVED DEVELOPMENT IS REQUIRED WHICH IS PRESENTED IN THE FOLLOWING PARAGRAPHS.

THERE ARE, IN THE ACTUAL CASE, OTHER SOURCES FOR DEVIATION OF THE POINT THAT A GIVEN RAY HITS THE TARGET. THESE INCLUDE:

1. THE ORIENTATION DEVIATION OF THE MIRROR AXIS WITH RESPECT TO THE LINE JOINING THE CENTER OF THE MIRROR AND THE CENTER OF THE SUN – φ.

2. THE ANGLE DEVIATION BETWEEN THE PARAXIAL RAY COMING FROM THE CENTER OF THE SUN AND THE RAY COMING FROM SOME OTHER POINT ON THE SUN'S DISK – γ.

THESE ARE SHOWN IN FIGURE 5. IN ORDER TO DETERMINE THE POINT OF THE TARGET ON WHICH A RAY FALLS LET US DEFINE TWO ANGLES δ_1', AND δ_2', WHICH ARE ANALOGOUS TO THE MIRROR ERRORS, δ_1, AND δ_2, BUT WHICH INCLUDE ALL OF THE SOURCES OF ERROR ON THE TARGET. BY SIMPLE GEOMETRY BASED ON FIGURE 5, THESE MAY BE FOUND AS FOLLOWS:

$$\delta_1' = \varphi \cos\theta + \gamma \cos(\theta - \beta) + 2\,\delta_1$$

$$\delta_2' = \varphi \sin\theta + \gamma \sin(\theta - \beta) + 2\,\delta_2$$

WHERE θ IS THE ANGULAR COORDINATE OF THE MIRROR

β IS THE ANGULAR COORDINATE OF THE SUN.

AGAIN BY ANALOGY WITH THE PREVIOUS DISCUSSION, THE TARGET ERROR CAN BE FOUND:

$$\frac{\mathcal{E}_1}{x_c f_1} = \frac{\varphi}{2}\cos\theta + \frac{\gamma}{2}\cos(\theta - \beta) + \delta_1$$

$$\frac{\mathcal{E}_2}{x_o f_2} = \frac{\varphi}{2}\sin\theta + \frac{\gamma}{2}\sin(\theta - \beta) + \delta_2$$

THE VALUES OF ε FORM A SET OF ROTATING COORDINATES ON THE TARGET, A FUNCTION OF θ, THE MIRROR COORDINATE. LET US CHOOSE A SET OF STATIONARY COORDINATES ON THE TARGET r, α, WHICH CAN BE DEFINED AS FOLLOWS:

$$\varepsilon_1 = r \cos(\theta - \alpha)$$

$$\varepsilon_2 = r \sin(\theta - \alpha)$$

WHERE r IS THE DISTANCE FROM THE FOCUS, α THE ANGULAR COORDINATE OF THE TARGET. THEN δ_1, AND δ_2, THE MIRROR ERRORS, CAN BE FOUND AS A FUNCTION OF THE OTHER VARIABLES.

$$\delta_1 = \frac{r}{f_1 X_c} \cos(\theta - \alpha) - \frac{\varphi}{2} \cos\theta - \frac{\gamma}{2} \cos(\theta - \beta)$$

$$\delta_2 = \frac{r}{f_2 X_c} \sin(\theta - \alpha) - \frac{\varphi}{2} \sin\theta - \frac{\gamma}{2} \cos(\theta - \beta)$$

NOW CONSIDER A DIFFERENTIAL AREA ON THE TARGET, $r\,dr\,d\alpha$ AND DETERMINE THE SOLAR ENERGY dQ WHICH FALLS THEREON. CONTRIBUTIONS WILL BE MADE FROM EVERY POINT ON THE SOLAR DISK, AND FROM EVERY POINT ON THE MIRROR, SO THAT FOUR INTEGRATIONS ARE REQUIRED.

$$dQ(r,\alpha) = \int_{\beta=0}^{2\pi} \int_{\gamma=0}^{\gamma_c} \int_{X=0}^{X_c} \int_{\theta=0}^{2\pi} \frac{K}{\pi \gamma_c^2}\, \gamma\, d\gamma\, d\beta\, x\, dx\, d\theta\, P_1 P_2\, d\delta_1\, d\delta_2$$

WHERE γ_c IS THE SUN'S HALF ANGLE.

K IS THE SOLAR INSOLENCE IN BTU/HRFT^2

$2X_o$ IS THE MIRROR DIAMETER

THE ERROR ANGLES, δ_1, AND δ_2, ARE A FUNCTION OF r, α, AND THE OTHER DEVIATION ANGLES, SO THAT THE EQUATION CAN BE REWRITTEN.

$$dQ(r,\alpha) = \int\!\!\int\!\!\int\!\!\int \frac{K}{\pi \gamma_c^2}\, \gamma\, d\gamma\, d\beta\, x\, dx\, d\theta\, P_1 P_2\, J\, dr\, d\alpha$$

WHERE J IS THE JACOBIAN OF THE TRANSFORMATION.

NOW dQ CAN BE REWRITTEN AS $K' r\,dr\,d\alpha$, WHERE K' IS THE FLUX ON THE SURFACE AT (r,α). THUS THE EQUATION FOR K' CAN BE EASILY FOUND AFTER A SUBSTITUTION FOR THE JACOBIAN:

$$K'(r,\alpha) = K \iiiint \left[\frac{\gamma\, d\gamma\, d\beta}{\pi\, \gamma_c^2}\right]\left[\frac{x\, dx\, d\theta}{f_1 f_2 X_c^2}\right]\left[P_1 P_2\right]$$

FROM THE PREVIOUS DEFINITION OF THE PROBABILITIES:

$$P_1 P_2 = \left[\frac{1}{2\pi\sigma^2}\right] \exp\left[-\frac{1}{2\sigma^2}\left(\delta_1^2 + \delta_2^2\right)\right]$$

$$= \frac{1}{2\pi\sigma^2} \exp -\frac{1}{2}\left\{\left[\frac{r}{\sigma f_1 X_0}\cos(\theta-\alpha) - \frac{\varphi}{2\sigma}\cos\theta - \frac{\gamma}{2\sigma}\cos(\theta-\beta)\right]^2 + \left[\frac{r}{\sigma f_2 X_0}\sin(\theta-\alpha) - \frac{\varphi}{2\sigma}\sin\theta - \frac{\gamma}{2\sigma}\sin(\theta-\beta)\right]^2\right\}$$

NO METHOD FOR PERFORMING THE FOUR INTEGRATIONS COULD BE FOUND. HOWEVER FOR PRACTICAL MIRRORS σ WILL BE ON THE ORDER OF 1°. SINCE φ CAN BE MAINTAINED WITHIN 0.1° AND THE AVERAGE VALUE OF γ IS 0.1°, φ AND γ CAN BE NEGLECTED IN THE PROBABILITY EXPRESSION. ROUGH CALCULATIONS INDICATE THAT NEGLECTING THESE TERMS FOR σ AS LOW AS 1/4° CAUSES ONLY A 10% ERROR IN THE DISTRIBUTION OF K'. THUS THE FINAL EQUATION WHICH WILL BE INVESTIGATED CAN BE WRITTEN AS FOLLOWS:

$$K'(r,\alpha) = \frac{K}{2\sigma^2}\iiiint\left[\frac{\gamma\, d\gamma\, d\beta}{\pi\, \gamma_c^2}\right]\left[\frac{x\, dx\, d\theta}{\pi X_c^2}\right]\left[\frac{1}{f_1 f_2}\right] \exp -\frac{1}{2}\left[\left(\frac{r}{\sigma f_1 X_c}\right)^2 \cos^2(\theta-\alpha) + \left(\frac{r}{\sigma f_2 X_c}\right)^2 \sin^2(\theta-\alpha)\right]$$

THIS CAN BE TRANSFORMED TO THE FOLLOWING EQUATION BY SUBSTITUTING THE HALF ANGLE FORMULAS.

$$K'(r,\alpha) = \frac{K}{2\sigma^2}\iiiint\left[\frac{\gamma\, d\gamma\, d\beta}{\pi\, \gamma_c^2}\right]\left[\frac{x\, dx\, d\theta}{\pi X_c^2}\right]\left[\frac{1}{f_1 f_2}\right] \exp -\left(\frac{r}{2\sigma X_c}\right)^2\left[\left(\frac{1}{f_1^2} + \frac{1}{f_2^2}\right) + \left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right)\cos 2(\theta-\alpha)\right]$$

INTEGRATIONS WITH RESPECT TO γ AND β ARE NOW EASILY CARRIED OUT. INTEGRATION WITH RESPECT TO θ CAN BE ACCOMPLISHED LEADING TO A HYPERBOLIC BESSEL FUNCTION OF f_1, f_2, AND X. INTEGRATION WITH RESPECT TO X IS VERY DIFFICULT BECAUSE OF THE VARIATION OF f_1 AND f_2 WITH X IN A VERY COMPLICATED MANNER. A GREAT SIMPLIFICATION RESULTS IF A SINGLE AVERAGE VALUE FOR f_1, AND f_2 IS ASSUMED, AND IF IT CAN BE SHOWN THAT THE SECOND TERM IN THE EXPONENTIAL HAS A SMALL EFFECT ON THE RESULT.

That the latter assumption is a good one can be seen from the fact that $\left[\frac{1}{f_1^2}+\frac{1}{f_2^2}\right]$ is much larger than $\left[\frac{1}{f_1^2}-\frac{1}{f_2^2}\right]$ and that $\cos 2(\theta-\alpha)$ changes sign twice over the integration and thus it does not add greatly to the final value of the integral. The final equation used for computation is then the following:

$$K'\left(\frac{r}{X_o}\right) = \frac{K}{2\sigma^2 f_m^2} \exp - \frac{1}{2}\left[\frac{r}{\sigma X_c f_m}\right]^2$$

The value of K' as a function of $\left(\frac{r}{X_c}\right)$ is plotted on Figure 6 for various values of σ. An average value of f_m equal to 2.5 was assumed for a 120 degree included mirror angle.

It will be noticed that the maximum heat flux varies as the inverse square of the normal deviation of the error angle. This is to be expected since the area on which the energy is distributed varies as the square of the deviation angle.

DETERMINATION OF COLLECTION EFFICIENCY

The collection efficiency will be defined for the purpose of discussion as the proportion of the energy leaving the mirror surface which stays within the cavity having the optimum sized aperture. Thus reradiation losses and the energy which falls outside the optimum sized hole are taken into account. To determine overall furnace factor (which is defined as the usable proportion of the solar energy which falls within the outer diameter of the mirror) such other factors as reflectivity, blockage, and seams must be taken into account.

In order to determine the efficiency, the curves of Figure 6 were replotted after being multiplied by the radius weight function, $\frac{r}{X_c}$, so that areas under the curve now represents energy and can be integrated graphically. The result is shown in Figure 7. The reradiation curves can also be plotted on the same set of axes for various constant collector temperatures such as would be found in a cavity type collector. Inasmuch as the area below the reradiation curve is the heat loss, the difference represents the heat absorbed and the collector efficiency is easily found for any combination of collector temperature and normal error. These efficiencies are shown in Figure 8, from which it will be noticed that at 1700° with an error of 1.0°, only 10% collector efficiency can be obtained, and that in order to get 80% collector efficiency, errors on the order of 0.35° are required.

A second curve is plotted in Figure 9 which shows the effect of a double boiler configuration on collector efficiency.

IT IS ASSUMED HERE THAT A CENTRAL CAVITY COLLECTS HEAT AT THE MAXIMUM TEMPERATURE (PLOTTED AS THE ABSCISSA) AND 75% OF THE ENERGY IS COLLECTED AT A TEMPERATURE 500° LOWER IN A SECOND CAVITY ARRANGED CIRCUMFERENTIAL AROUND THE CENTRAL CAVITY. HERE AT 1700°F, A 1.0° ERROR GIVES 63% EFFICIENCY, AND 80% EFFICIENCY IS OBTAINABLE WITH AN 0.7° ERROR.

CONCLUSIONS

IT IS NOT THE PRIMARY PURPOSE OF THIS PAPER TO DISCUSS THE PRACTICABILITY OF LARGE SCALE DEPLOYABLE MIRRORS FOR SPACE POWER PLANTS. TOO LITTLE HAS BEEN ACCOMPLISHED ON THE DEVELOPMENT OF SUCH UNITS TO ALLOW A SIGNIFICANT DISCUSSION OF WHAT GEOMETRIC ACCURACY CAN BE MAINTAINED IN LARGE UNSUPPORTED SHEET METAL OR FOAMED PLASTIC STRUCTURES. HOWEVER, THE RESULTS OF THIS ANALYSIS DO LEAD TO CERTAIN TENTATIVE CONCLUSIONS BASED ON THE PRESENT STATE OF THE ART, UNDEVELOPED AS IT IS.

1. MIRRORS FOR RANKINE CYCLE POWER PLANTS WITH BOILING (OR HEAT STORAGE) TAKING PLACE AT 1250°F ARE PROBABLY PRACTICAL NOW, AT LEAST IN REASONABLE SIZES, SINCE THE REQUIRED MIRROR ACCURACIES ARE ON THE ORDER OF 1°. SUCH ACCURACIES CAN BE OBTAINED WITH EXPLOSION OR STRETCH FORMING ON PIECES UP TO FIVE OR SIX FEET IN LENGTH PROVIDED ACCURATE POSITIONING DEVICES ARE DEVELOPED. THIS WOULD INDICATE THAT DEPLOYABLE MIRRORS 22 FEET IN DIAMETER ARE POSSIBLE VERY SOON (2 SIX FOOT LEAVES PLUS A 10 FOOT CENTRAL SECTION).

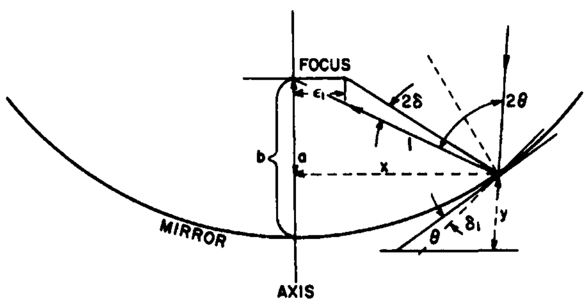
2. MIRRORS WHICH OPERATE AT TEMPERATURES HIGHER THAN 1700°F SEEM TO REQUIRE A DEFINITE ADVANCE IN THE STATE OF THE ART. FOR TEMPERATURES OF 2600°F AND ABOVE SUCH AS THOSE CONTEMPLATED FOR THERMIONIC SYSTEMS, ACCURACIES WELL BELOW 1/4° ARE REQUIRED. IT SEEMS HARD TO BELIEVE THAT THESE CAN EVER BE OBTAINED IN ANY DEPLOYABLE SYSTEM; IT IS PROBABLE THAT INTEGRAL SPUN SHEET METAL DISH TYPE REFLECTORS ARE REQUIRED. THESE WILL BE LIMITED BY THE VEHICLE DIMENSIONS TO WELL BELOW 1000 WATTS OUTPUT FOR EACH MIRROR.

3. REFLECTORS FOR LARGE, MODERATE TEMPERATURE, SYSTEMS STILL REQUIRING ACCURACIES ON THE ORDER OF 1°, WILL REQUIRE DOUBLE FOLDS AND LARGER SECTIONS THAN ARE NOW BEING MADE. SUBSTANTIAL DEVELOPMENT PROGRAMS ARE REQURED TO SUPPORT THIS WORK TO ASSURE FEASIBLE SYSTEMS IN THE NOT TOO DISTANT FUTURE.

IT WILL BE NOTICED THAT NO MENTION IS MADE OF GAS DEPLOYED, FOAM SUPPORTED, PLASTIC FILM REFLECTORS. THE AUTHOR IS NOT FAMILIAR WITH ANY PUBLISHED ANALYSIS OF GEOMETRICAL ACCURACIES POSSIBLE WITH THIS TYPE OF REFLECTOR.

REFERENCES

1. Hiester, N. K., Tietz, T. E., Loh, E., Duwez, P., "Solar Furnace Performance", Jet Propulsion, Volume 27, 1957, p. 507.



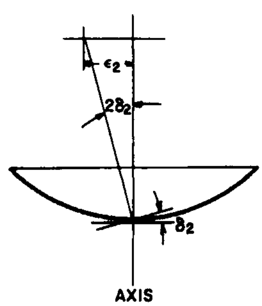


FIGURE I.
MIRROR GEOMETRY

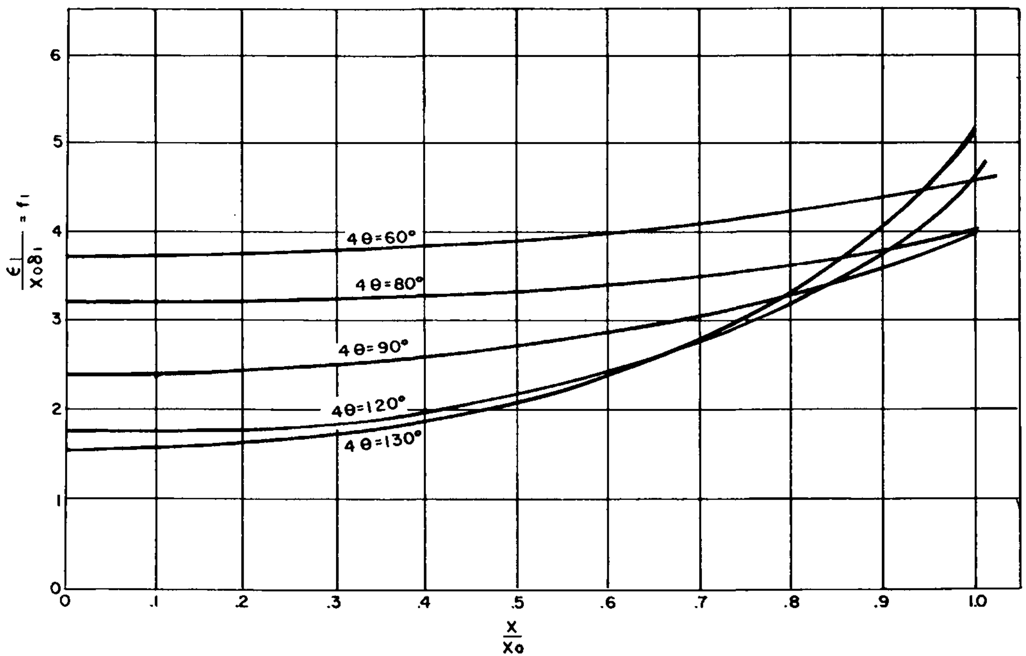


FIGURE 2.
ACCURACY EFFECT OF RADIAL ANGLE EFFECT

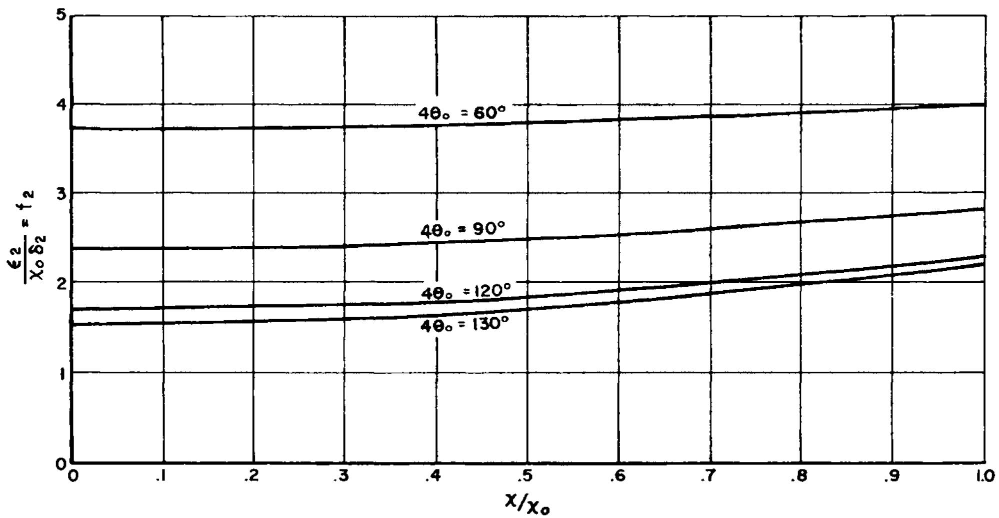


FIGURE 3.
ACCURACY EFFECT OF TANGENTIAL ANGLE ERROR

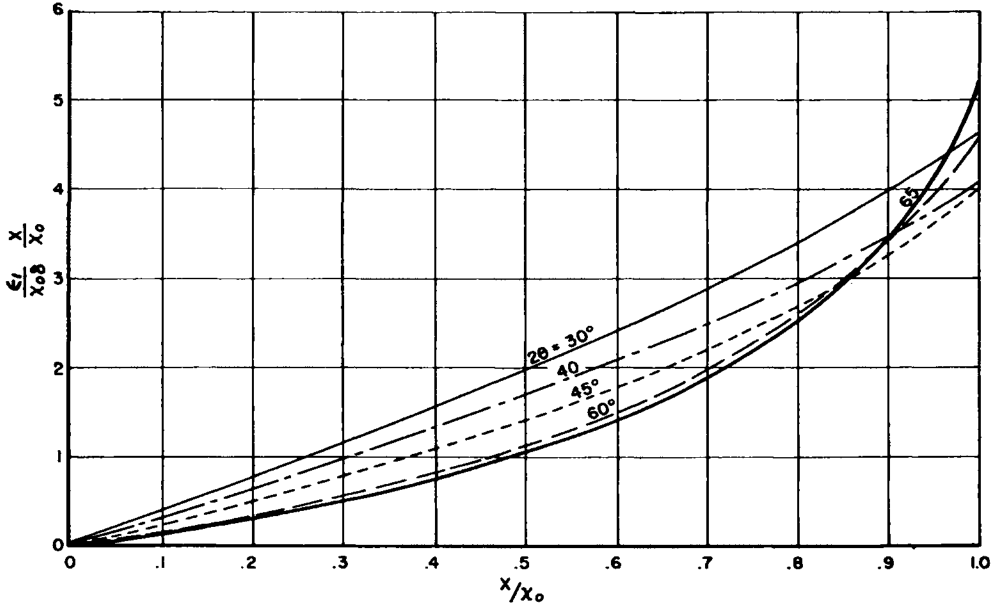


FIGURE 4.
WEIGHTED ACCURACY EFFECT OF ANGLE ERROR

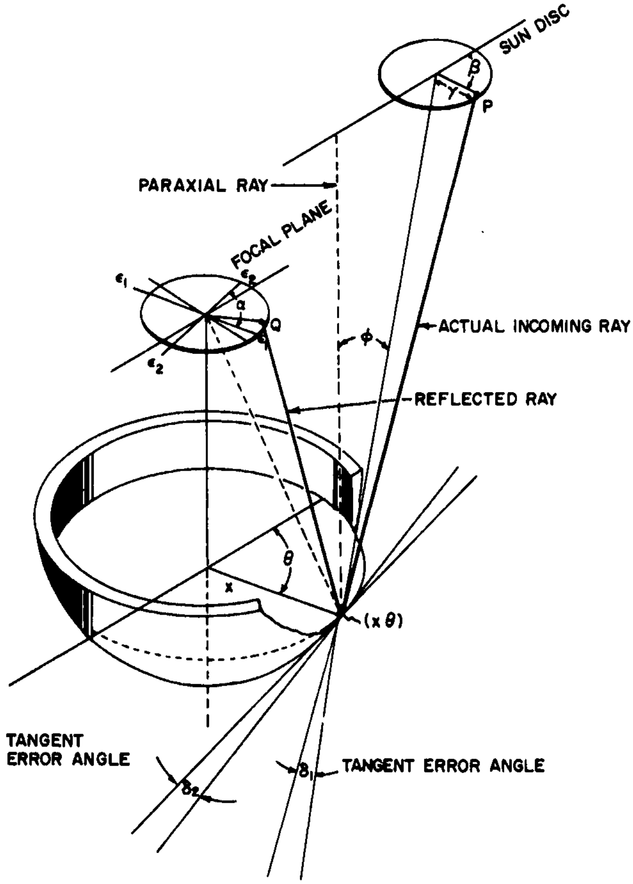


FIGURE 5.
GEOMETRICAL REPRESENTATION OF SOLAR RAYS
FOR PARABOLOID CONCENTRATOR

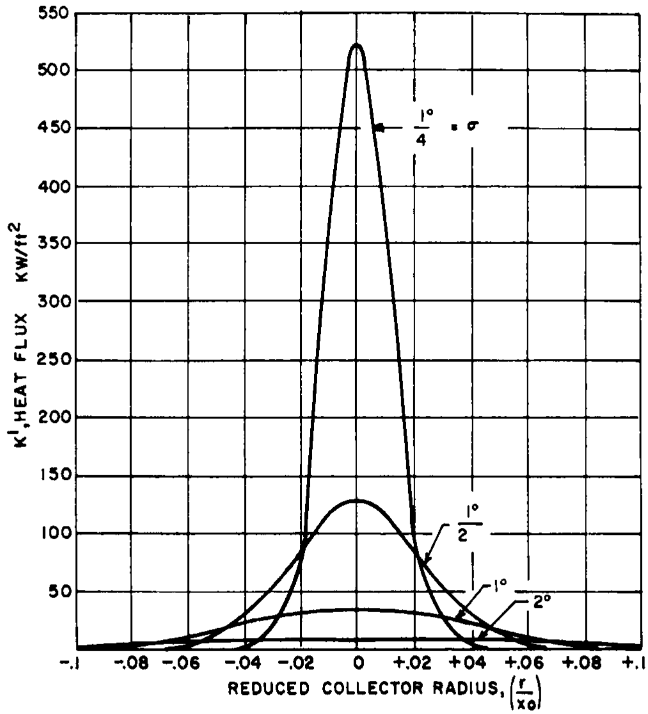


FIGURE 6.
HEAT FLUX FROM A CONCENTRATING MIRROR

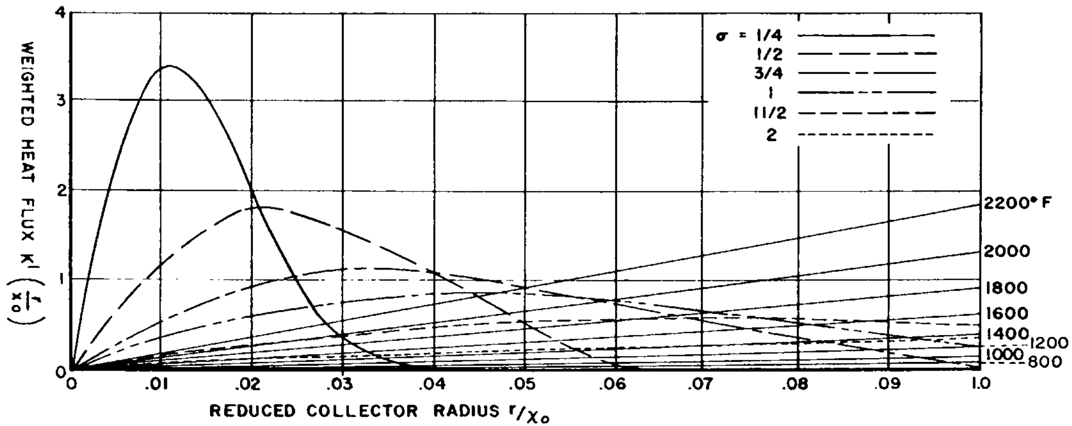


FIGURE 7.
WEIGHTED HEAT FLUX FROM A CONCENTRATING MIRROR

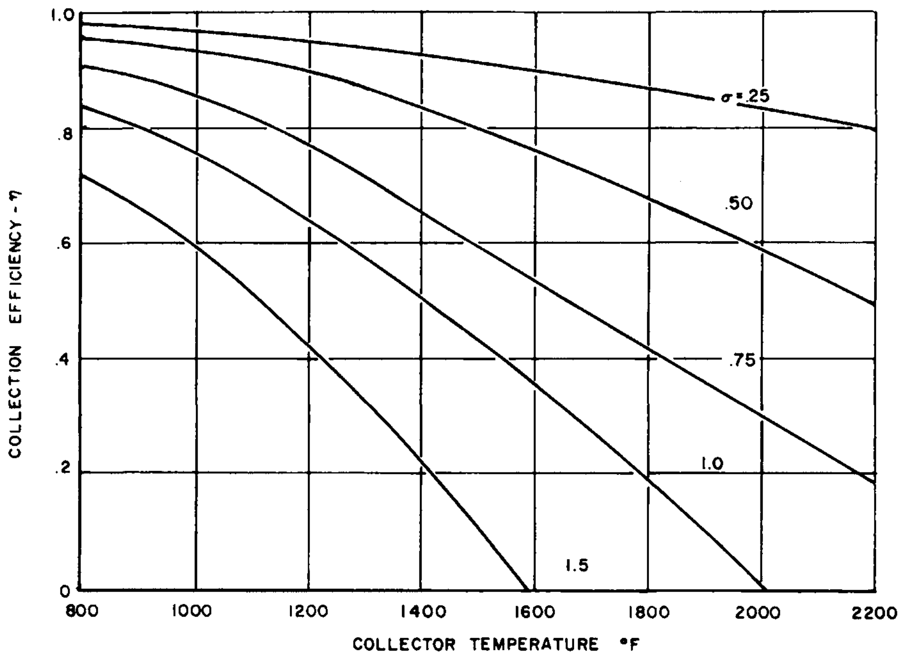


FIGURE 8.
EFFICIENCY OF BLACK BODY CAVITY BOILER

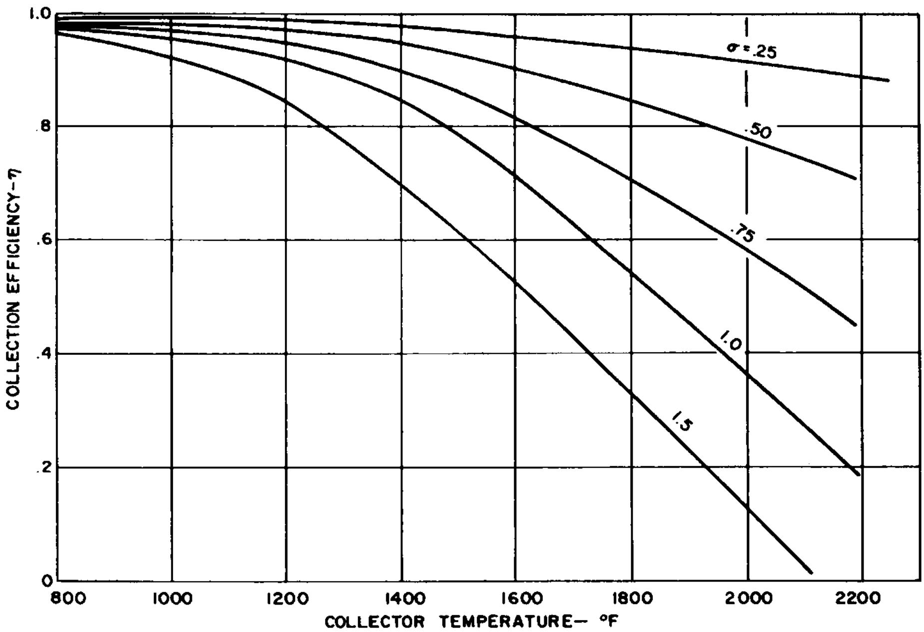


FIGURE 9.
EFFICIENCY OF DOUBLE CAVITY BOILER