CONSTRUCTION AND TEST OF A SOLAR FURNACE

by

JAMES ELMER BODINE JR.

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APPROVED:

Redacted for privacy

Assistant Professor of Chemical Engineering
In Charge of Major

Redacted for privacy

Head of Department of Chemical Engineering

Redacted for privacy

Chairman of School Graduate Committee

Redacted for privacy

Dean of Graduate School

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Typed by Maritza Bodine
and James Bodine

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

FIGURES

TABLES

CONSTRUCTION AND TEST OF A SOLAR FURNACE

INTRODUCTION

The sun is a celestial body which has been of importance to man since his creation. Besides the warmth which the sun's radiant energy has supplied daily, the radiant energy from the sun has also been responsible for the fossil fuels of which we are so dependent at home and in industry.

The source of this radiant energy, the sun, has a surface temperature of approximately 6000 degrees Kelvin. The amount of radiant energy which the earth receives per square mile of surface area from this ultra-high temperature source is equivalent to about 5,000,000 horse power when the sun is directly overhead.

Methods are being devised for economic utilization of a part of this vast energy both to conserve our dwindling supply of natural fuels and against the day when our supply of natural fuels is depleted. A great deal of work has been done toward development of processes utilizing solar radiation both through non-concentration and concentration of the radiation; however additional work still remains to be done before economic utilization is achieved.

It has come across the minds of many men that it should be possible, here on earth, to approach the ultra-high temperature of the sun's surface and it is toward this end that means to concetrate the sun's radiation have been devised through the use of lenses and mirrors. As we are yearly advancing toward the use of higher temperatures we must devise means to evaluate materials that may be used to contain these ever mounting temperatures. Besides investigating the high temperature properties of materials we are also interested in obtaining super-pure materials. Even very slight amounts of impurities on the order of parts per million can greatly affect the properties of materials. Purification techniques in current practice require extremely high temperatures in order to remove all impurities. It is primarily for these two reason that solar furnaces are being used.

A solar furnace project was initiated here at Oregon State College to evaluate the feasibility of concentrating the sun's radiant energy in order to produce a high temperature source for inorganic chemical investigations. The specific project in mind was purification of boron by zone refining, (i. e., partial refining, bit by bit, to a higher and higher purity by alternately melting and freezing the sample).

HISTORY OF SOLAR FURNACES

It is generally conceded that Archimedes, in 215 or 212 B. C., was the first to attain elevated temperatures by the use of solar radiation. He is reputed to have burned the Roman fleet which blockaded Syracuse by concentrating the sun's rays and focusing them on the ships (2, p.56; 8, pp.157-158; 10, p.3). Similarly, it is conceded that Procus, in 614 A. D., by the use of brass mirrors, burned the fleet beseiging Constantinople (8, p.158).

Another early record reports the use of concentrated radiation by the Athenians to light the sacred fires of Vesta by means of a polished concave gold surface (8, p.158). In the 17th century an optician named Villete of Lyons, France constructed several solar furnaces with polished iron mirrors. These solar furnaces were used in France, Denmark, Persia and other countries (1, p.53). In 1695 Averani and Targioni, at Florence, Italy, used a large burning glass to make a diamond, previously considered unalterable, disappear (8, p.158). A large number of lenses and concave mirrors were made during this same period and a number of fusions and combustions were studied (8, p.158). Around 1700, Tschirnaus was able to melt slate, china, talc, and tile with a 0.97 meter diameter lens (8, p.158).

In the 18th century Buffon, superimposing the images reflected from a number of small flat mirrors, was able to melt some metals and kindle wood (1, p. 53; 8, p.158).

Lavoisier, in the 1770's, by arranging 2 lenses in series was able to attain temperatures of about 3200°F. The lenses were reputed to be merely 2 pieces of glass filled with wine (1, p.64; 2, p.56; 8, p.158).

The present era might be considered as having begun with the construction of a small 2-lens, adjustable mounting, enclosed sample solar furnace by Stock and Heyneman in the early 1900's (8, p.158).

In the 1920's the Zeiss company at Jena, Germany constructed several solar furnaces of various configurations (4, p.915; 8, p.160). California Institute of Technology, in 1932, constructed a solar furnace using only lenses and mirrors (4, p.915).

Since World War II several dozen solar furnaces have been constructed all over the world but principally in France and the United States. France has at least 8 solar furnaces including one at Bouzareah, Algiers. References list more than twenty solar furnaces in the United States (6, Table II; 8, p.166).

GEOMETRICAL CONFIGURATIONS OF SOLAR FURNACES

Up to the present time solar furnaces have been constructed with a number of geometrical configurations for mounting the reflectors. Some of these configurations are described below.

The altazimuth mounting is the standard type of mirror mounting used for military searchlights. It may be seen in Figure 1 that elevation of the mirror is achieved by rotation about the axis drawn through each side of the mirror, while horizontal movement is effected by a single pivot below. The three pivots lie in a single vertical plane (1, p.12).

There are four pivot points, all lying in the same inclined plane, in the equatorial mounting. As shown in Figure 2, the upper and lower pivots provide horizontal movement while pivots at the midpoint of the sides of the mirror provide variation in elevation (1, p.54).

Several arrangements are possible using a heliostat. A heliostat is defined as a reflector which tracks the sun and reflects the sun's rays in a fixed direction. In Figure 3-A the parabolic concentrator is mounted in a vertical position with its axis horizontal. This is the geometrical configuration to be found in the largest solar furnaces constructed to date or under construction.

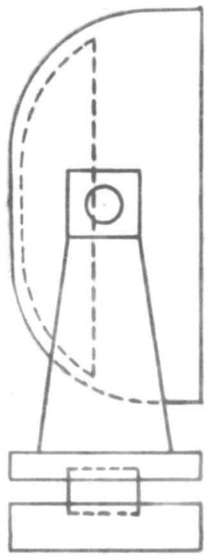

FIGURE 1

ALTAZIMUTH MOUNTING

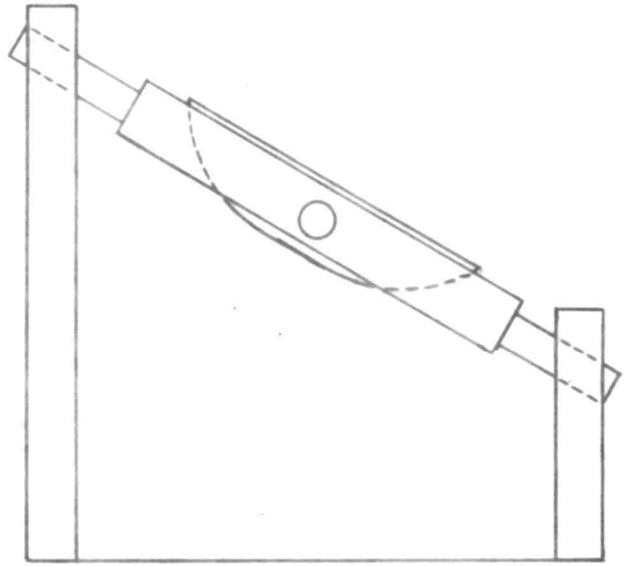

FIGURE 2

EQUATORIAL MOUNTING

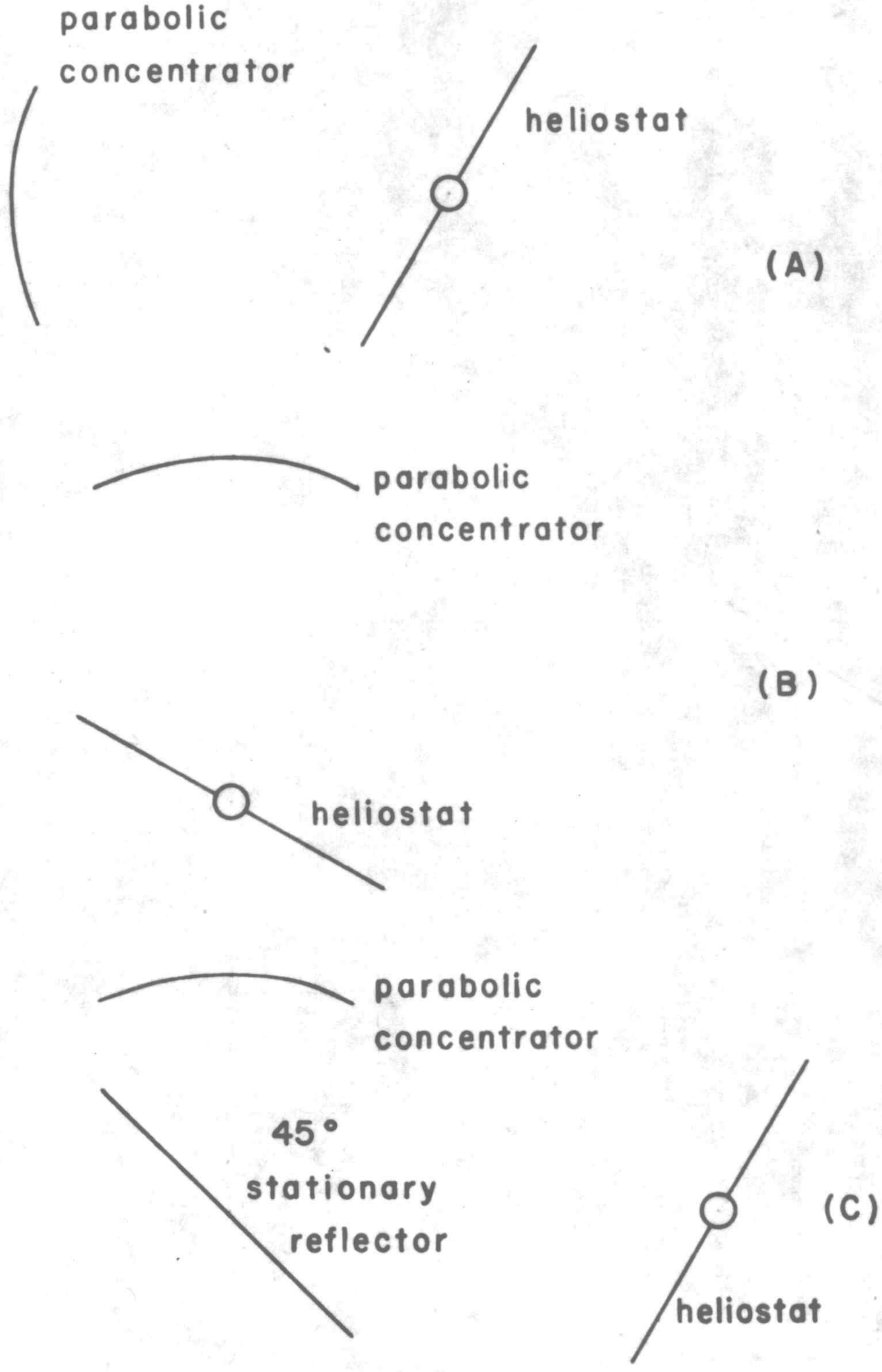

FIGURE 3 HELIOSTAT MOUNTINGS

The parabolic concentrator in these installations consists of a large number of plane or curved mirror segments (3, p.4; 13, p.57). The parabolic concentrator may also be mounted in a horizontal position with its axis vertical as shown in Figure 3-B and 3-C. In Figure 3-B the heliostat is located directly below the concentrator (13, p.61) while in Figure 3-C a plane mirror is mounted below the concentrator at a 45 degree angle and the heliostat reflects the sun's rays onto this 45 degree reflector which reflects to the concentrator (see Figure 4).

A system composed of lenses and mirrors for concentration of the sun's rays is shown in Figure 5. This was the first solar furnace constructed in the United States. The sun's rays are refracted and partially concentrated by an initial group of lenses onto mirrors which reflect the rays through an almost hemispherically arranged group of smaller lenses (4, p.919).

For the Newtonian type of mounting as shown in Figure 6, the sun's rays impinge on a parabolical concentrator reflecting to a flat plate which in turn reflects to a lens which provides the final concentration.

It is seen in Figure 7 that the Cassegrainian type of mounting consists of a two stage concentration, the first stage being reflected from a concave mirror

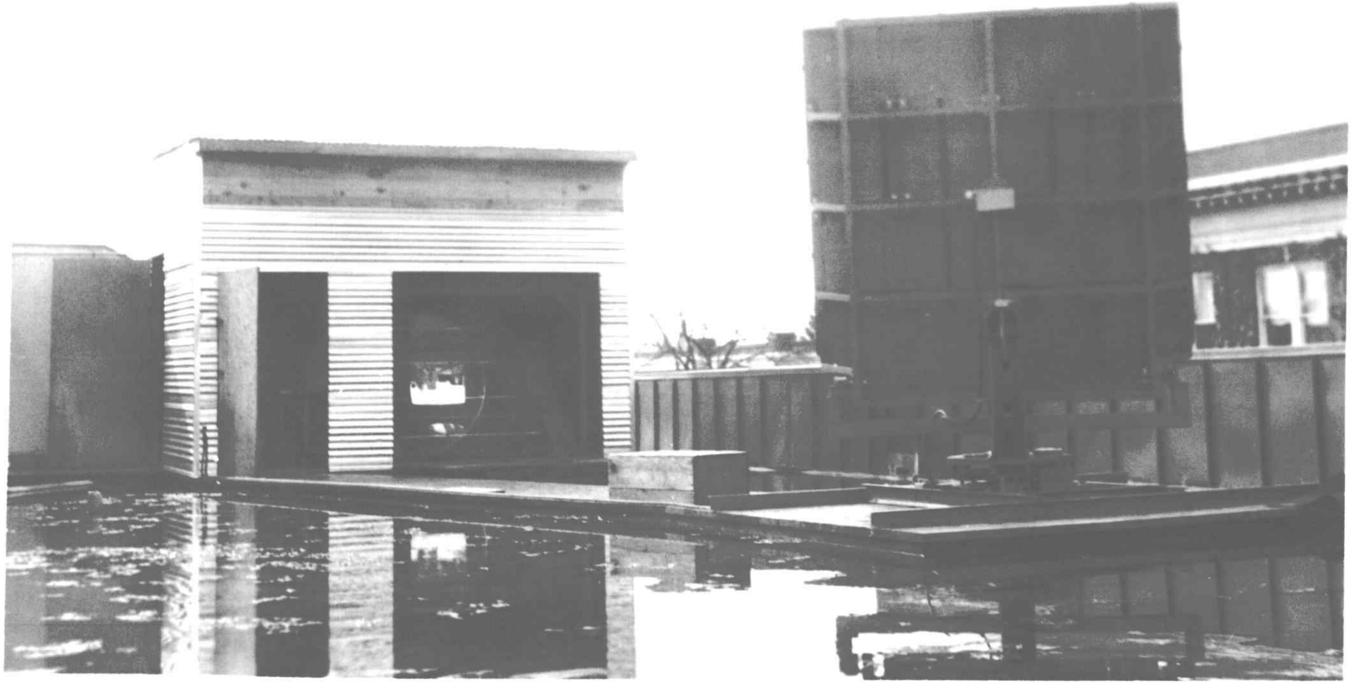

FIGURE 4 THE OREGON STATE COLLEGE SOLAR FURNACE

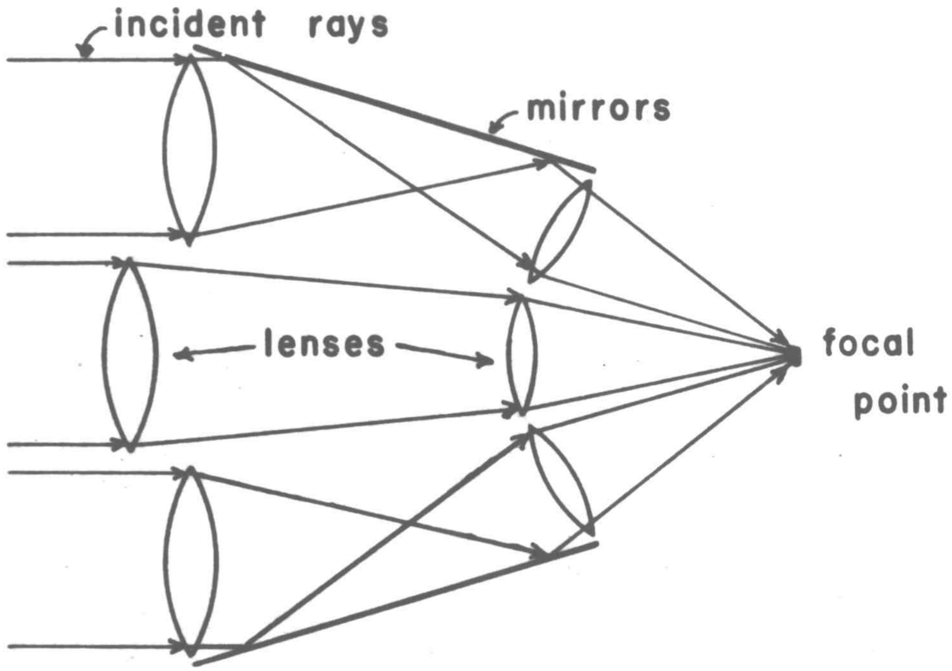

FIGURE 5 MOUNTING OF LENSES AND MIRRORS

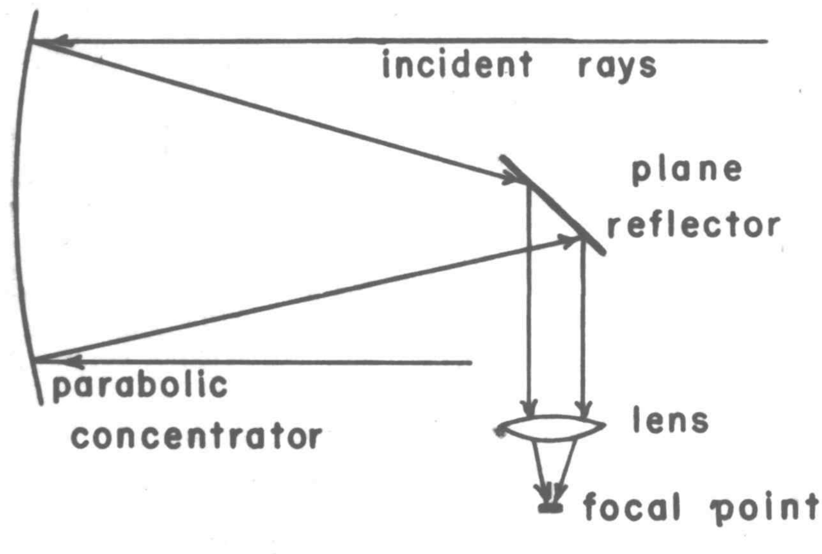

FIGURE 6 NEWTONIAN MOUNTING

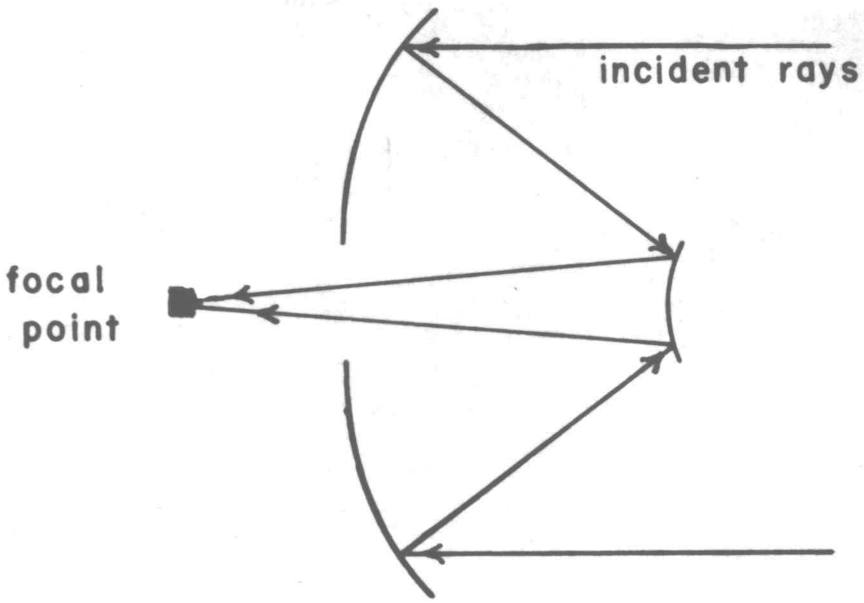

FIGURE 7 CASSEGRAINIAN MOUNTING

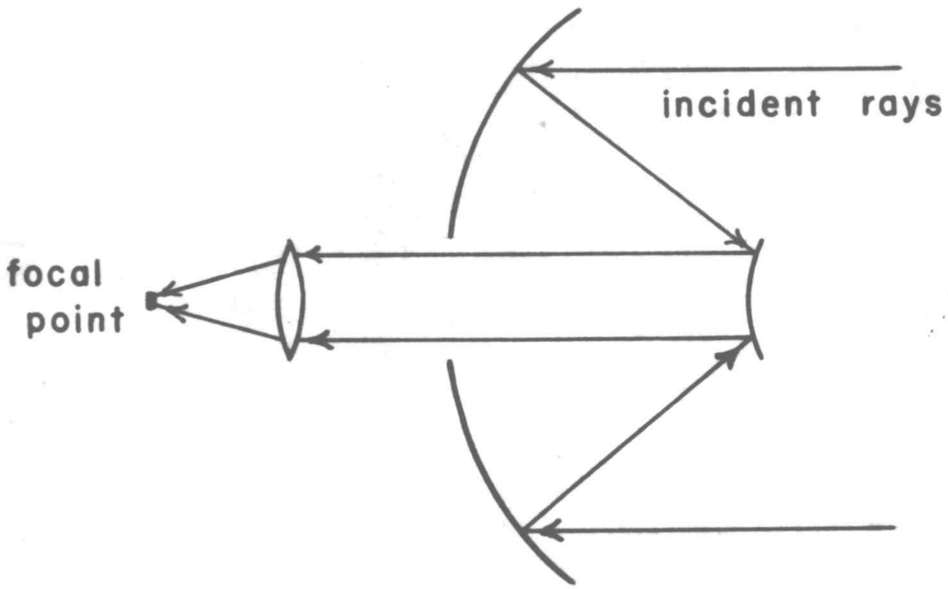

FIGURE 8 STRAUBEL 2-STEP MOUNTING

and the second stage being reflected from a convex mirror to the target which is located behind the first stage concentrator (13, p.62).

The Straubel two-step mounting is a variation of the Cassegrainian mounting. It is seen in Figure 8 that the rays reflected from the secondary convex reflector are parallel to each other. They then pass through a converging lens to the target (1, p.54).

A system consisting of several hundred three inch plane mirrors has been constructed. This system, with its special mounting of each mirror has been called "oriented flat plates".

The most popular configurations in the United States at the present time are the altazimuth mounting and the heliostat mounting. It is interesting to note that the majority of the solar furnace installations in the United States are utilizing surplus military searchlights with a 60 inch diameter parabolic mirror. Also, the heliostat mounting appears to be gaining favor so that advantage may be taken of the stationary paraboloid and the fixed focal spot.

Table 1 contains data from a number of solar furnace installations.

TABLE 1

A Partial Survey of Solar Furnaces

Organization	A. D. Little, Inc.	Arizona State College	Bureau of Mines
Furnace location	Cambridge, Mass.	Tempe, Arizona	Morgantown, W. Va.
Furnace description			
Main mirror			
Mounting	Altazimuth	Fixed; axis horiz.	Altazimuth
Mirror material	Copper	Copper	Copper
Reflecting surface material	Stellite	Aluminum	Rhodium
Reflecting surface	Front	Front	Front
Aperture	59.5 in.	60 in.	60 in.
Focal length	25.6 in.	29.5 in.	26 in.
Rim angle	60° 15'	65°	
Theoretical image diameter	0.236 in.	0.238 in.	
Auxiliary mirrors and lenses			
No. of aux. mirrors	None	One	None
No. of lenses	None	None	None
System		Heliostat	
Tracking	Manual	Phototubes	Manual
Maximum temperature obtained		3300 K	2760 K
Maximum flux measured		300 cal/cm^2/sec (est)	
Ave. local solar const.	1.3 cal/cm^2/min	1.1 cal/cm^2/min	
Reflectivity factor	75% (est.)	75% (heliostat)	
Shadowing factor	96.4%	96%	85%
Source of information	6	6	6

TABLE 1 (Continued)

Organization	Calif. Inst. of Tech.	Convair	Convair
Furnace location	Pasadena, Calif.	San Diego, Calif.	Ft. Worth, Texas
Furnace description			
Main mirror			
Mounting	Equatorial	Altazimuth	Equatorial
Mirror material		Copper	Aluminum
Reflecting surface material		Co-Ni alloy	Same
Reflecting surface		Front	Front
Aperture		60 in.	120 in.
Focal length		25.5 in.	34.5 in.
Rim angle		60°	82°
Theoretical image diameter	0.50 in.	0.24 in.	0.32 in.
Auxiliary mirrors and lenses			
No. of aux. mirrors	18	None	None
No. of lenses	38	None	None
System			
Tracking	Astron. control	Manual	Astron. control.
Max. temperature obtained	3200 ± 100° C.	3050° C.	2800° C.
Maximum flux measured	170 cal/cm^2/sec	629 cal/cm^2/sec	139 cal/cm^2/sec
Ave. local solar const.		1.3 cal/cm^2/min	
Reflectivity factor		85%	
Shadowing factor		63%	
Source of information	6	6	6

TABLE 1 (Continued)

Organization	E. I. du Pont de Nemours & Co.	Fordham University	Kennecott Copper Corp.
Furnace location	Wilmington, Del.	New York, N. Y.	Salt Lake City, Utah
Furnace description			
Main mirror			
Mounting	Altazimuth	Altazimuth	Fixed; axis vert.
Mirror material	Copper	Bronze	Copper
Reflecting surface material	Rhodium	Stellite	Rhodium
Reflecting surface	Front	Front	Front
Aperture	60 in.	60 in.	60 in.
Focal length		25.5 in.	25.8 in.
Rim angle		60.8°	60°
Theoretical image diameter		0.238 in.	0.24 in.
Auxiliary mirrors and lenses			
No. of aux. mirrors	None	None	2
No. of lenses		None	None
System			Heliostat
Tracking	Manual	Phototubes	Phototubes
Maximum temperature obtained	3000°C.	3500°C.	2800°C.
Maximum flux measured			
Ave. local solar const.			
Reflectivity factor		70% (meas.)	70% (est.)
Shadowing factor		96% (meas.)	95% (app.)
Source of information	6	6	6

TABLE 1 (Continued)

Organization	Massachusetts Inst. of Tech.	National Bureau of Standards	Oregon State College
Furnace location	Cambridge, Mass.	Washington, D. C.	Corvallis, Ore.
Furnace description			
Main mirror			
Mounting	Special	Fixed; axis horiz.	Fixed; axis vert.
Mirror material	Glass	Copper	Copper
Reflecting surface material	Silver	Rhodium	Rhodium
Reflecting surface	Back	Front	Front
Aperture		60 in.	60 in.
Focal length		26 in.	26 in. (app.)
Rim angle		60°	60° (app.)
Theoretical image diameter	3 in.	0.25 in.	0.242 in. (app.)
Auxiliary mirrors and lenses			
No. of mirrors	One	One	2
No. of lenses	None		None
System	Special	Heliostat	Heliostat
Tracking		Phototubes	Photocells
Maximum temperature obtained		3300°C.	
Maximum flux measured			
Ave. local solar const.	1.5 cal/cm^2/min		
Reflectivity factor	60% (est.)		
Shadowing factor			
Source of information	6	6	

TABLE 1 (Continued)

Organization	Quartermaster R & D command	Stanford Research Inst.	University of Minnesota
Furnace location	Natick, Mass.	Menlo Park, Calif.	Minneapolis, Minn.
Furnace description			
Main mirror			
Mounting	Fixed; axis horiz.	Fixed; axis vert.	Altazimuth
Mirror material	Glass	Copper	Copper
Reflecting surface material	Aluminum	Rhodium	Rhodium
Reflecting surface	Front	Front	Front
Aperture	28 ft. x 28 ft.	60 in.	60 in.
Focal length	35.8 ft.	26 in.	
Rim angle	32°		
Theoretical image diameter	4 in.	0.25 in.	
Auxiliary mirrors and lenses			
No. of mirrors	One	One	None
No. of lenses			
System	Heliostat	Heliostat	
Tracking	Phototubes	4 phototubes	Manual
Max. temperature obtained			
Maximum flux measured			
Ave. local solar const.			
Reflectivity factor			
Shadowing factor			
Source of information	6	6	6

TABLE 1 (Continued)

Organization	University of Delaware	WMC Prec. Works & RMF Steel Prod.	CNRS
Furnace location	Newark, Del.	Kansas City, Mo.	Mont Louis, France
Furnace description			
Main mirror			
Mounting	Altazimuth	Equatorial	Fixed; axis horiz.
Mirror material	Copper	Copper	3500 glass plates
Reflecting surface material	Rhodium	Rhodium	Silver
Reflecting surface	Front	Front	Back
Aperture	60 in.	60 in.	35.0 ft.
Focal length	26 in.	26.3 in.	19.7 ft.
Rim angle	60°		
Theoretical image diameter	0.25 in.	0.236 in.	2.2 in.
Auxiliary mirrors and lenses			
No. of mirrors			One
No. of lenses			
System			Heliostat
Tracking	Manual	Phototubes	Photocells
Maximum temperature obtained	3000°C. (app.)	3000°C.	3000°C. (app.)
Maximum flux measured			
Ave. local solar const.	1.35 cal/cm^2/min		1.43 (assum. 4)
Reflectivity factor		86%	70% (assum. 4)
Shadowing factor		95%	
Source of information	6	6	4,8

TABLE 1 (Continued)

Organization	CSRSAA	ZEISS (?)
Furnace location	Bouzareah, Algiers	Jena, Germany
Furnace description		
Main mirror		
Mounting	Equatorial	Fixed
Mirror material	Aluminum	Glass
Reflecting surface material	Aluminum	Silver
Reflecting surface	Front	Back
Aperture	27.6 ft.	6.55 ft.
Focal length	10.3 ft.	2.82 ft.
Rim angle		
Theoretical image diameter	1.15 in.	0.315 in.
Auxiliary mirrors and lenses		
No. of mirrors		One (?)
No. of lenses		
System		Heliostat
Tracking		
Maximum temperature obtained	3000°C.	
Maximum flux measured		
Ave. local solar const.	1.43 (assum. 4)	
Reflectivity factor	80% (assumm. 4)	
Shadowing factor		
Source of information	1,4	5,8

ADVANTAGES AND USES OF SOLAR FURNACES

While a solar furnace has a maximum theoretically obtainable temperature of about 4000 degrees Kelvin (8, p.160) as opposed to other means of obtaining temperatures up to tens of thousands of degrees, nevertheless, the temperatures achievable appear rather high when compared with the few materials capable of withstanding even 3000 degrees Kelvin. The solar furnace thus is capable of producing high temperatures, in controllable atmospheres, free from combustion products, heated furnace walls, and electric or magnetic fields. Furthermore, in some of the geometrical arrangements, a sample being melted can serve as its own receptacle thus eliminating the necessity for ultrahigh temperature crucible materials and possible contamination. A solar furnace can deliver heat to a surface at a rate exceeding that found in rocket motors and even up to perhaps half of the heat that is found in nose cones of missiles re-entering the atmosphere.

The intensity of radiation concentrated and consequently the temperature obtained may be controlled by a diaphragm or shutters (shades), a reflecting cylinder, or by defocusing. Visual observations of the sample may be made up to the maximum temperature. On the debit side is the fact that a solar furnace may be used only during the day and is dependent on favorable atmospheric conditions.

Fields of study are many and varied. A few of these would include the following: studies of the high-temperature chemistry and physics of metals, alloys, refractories, cermets, and ceramics for evaluation of their properties to help ascertain practical uses of these materials; preparation of special materials or pure substances for evaluation of their properties or to satisfy specific requirements.

FACTORS TO BE CONSIDERED IN THE DESIGN OF A SOLAR FURNACE

The many factors which should be considered when designing a solar furnace can be classified into six general categories: 1) type of furnace, 2) mounting and tracking, 3) optics, 4) materials and accuracy of construction, 5) geographical location, and 6) type of target or use.

Although all of the factors which are outlined below should be considered when designing a solar furnace it may be found, as in the case of the furnace from which this thesis was prepared, that few alternatives are available if the furnace is to be used for a particular application and a geographical location is stipulated.

TYPE OF FURNACE

By type of furnace is meant the method by which the sun's rays are captured and concentrated. There are three main types of concentrators: lenses and mirrors, oriented flat plates, and parabolic or hemispherical surfaces made up of a single reflecting surface or curved mirror segments.

The usual practice has been that concentrators that track the sun have been of one piece construction with very few exceptions. Where the concentrator is stationary it may be either one piece or composed of plane or curved mirror segments. The practice has been to use one piece parabolic concentrators up to perhaps ten feet in diameter and to use curved mirror segments for larger dimensions.

With the exception of curved mirror segments, these types of furnace have been discussed previously. By curved mirror segments is meant applying a mechanical deformation. By applying pressure at carefully chosen points on the front and back of a mirror, it may be deformed to the curvature of a paraboloid or hemisphere. Thus, very large concentrators may be built up by mounting a number of these curved mirror segments side by side.

MOUNTING AND TRACKING

The method by which the concentrator is mounted to follow the sun's path or the method by which the sun's rays are reflected to a fixed concentrator are found under the classification mounting and tracking. These various types are where: 1) individual flat-plate mirror segments each track the sun and horizontally reflect the rays which are superimposed on the target; 2) the entire concentrator follows the sun's path; 3) the concentrator is fixed with its axis horizontal and the sun's rays are reflected to the concentrator by a heliostat; 4) the concentrator is fixed with its axis vertical and a heliostat is used; 5) the concentrator is fixed with its axis vertical and mounted over a stationary plane reflector mounted at 45 degrees into which a heliostat reflects the sun's rays.

OPTICS

By optics is meant the optical geometry of the concentrator. The important variables of the concentrator included in this group are: 1) aperture, the diameter of the concentrator measured across the rim, 2) ratio of aperture to focal length (the distance from the concentrator that the reflected rays converge to a point), 3) image or target diameter, the size of the image formed at the focal point, 4) average target flux, the heat received at the focal point per unit area, and 5) uniformity of flux distribution at the target, the variation of heat from point to point in the target area.

MATERIALS AND ACCURACY OF CONSTRUCTION

The materials to be used for reflecting and concentrating the sun's rays must be considered inasmuch as the reflectivity of materials varies. The first consideration then is reflector materials. Next is found a factor which represents the accuracy of construction or the geometrical perfection of the furnace as a whole. This factor is denoted by γ. Last is found an overall efficiency factor, E, which is the ratio of the actual amount of energy concentrated to the amount of energy which theoretically should have been concentrated. As will be seen later this efficiency factor takes into account all imperfections and losses in the transmission and concentration of the energy originally received at the edge of the earth's atmosphere.

GEOGRAPHICAL LOCATION

When selecting the geographical location it is of the utmost importance to consider both the total radiation received at the proposed site and the amount of pollutants and water vapor usually found in the atmosphere. As will be shown later, only a part of the total radiation is utilizable and this part is proportional to the clarity of the atmosphere. While the amount of radiation which is received increases as one approaches the equator or goes to higher altitudes, this advantage may be more than overcome by high humidity and haze in the atmosphere. For this reason then, clarity of the atmosphere is of greater importance than the latitude or elevation of the site.

TYPE OF TARGET, OR USE

The maximum obtainable temperature is dependent on the emissivity or absorptivity of the target and the heat losses by convection and conduction; consequently, the size, shape, and material of the target must be considered. Of consideration also is the desired use of the furnace, i. e. as a high temperature source or as a production unit, to determine the work space needed and the type of mounting.

In the Oregon State College solar furnace a parabolic searchlight reflector was chosen for the concentrator. This was mounted on the roof of the chemical engineering building. Consequently, the type of furnace, optics, and location were fixed. Furthermore, the parabolic reflector, with its axis vertical, was designed for mounting over a 45 degree angle plane reflector with a heliostat to track the sun. This geometrical configuration allowed the sample being melted to serve as its own receptacle. Back silvered mirrors were to be used. As a consequence, the factors mounting and tracking and reflector materials as well as the reflectivity factor, η_r, were fixed.

Those factors which limit the degree of concentration of energy and consequently the maximum attainable temperature are: 3) Optics, 4) Materials and accuracy of construction, 5) Location, and 6) Type of target. These factors will be related to the actual solar furnace as constructed.

DISCUSSION OF LOCATION

A long series of solar energy measurements has given a value of approximately 1.95 calories/minute/square centimeter of surface normal to the sun's rays before depletion by the atmosphere as the amount of radiation received by the earth from the sun. This quantity is referred to as the solar constant and it represents an incidence of solar energy on the earth, when the sun is directly overhead, of about 5,000,000 horsepower per square mile. Only a part of this insolational energy reaches the ground for utilization with a solar furnace. It is estimated that 43% of the incident insolational energy is reflected back to space. This figure of 43% is referred to as the albedo, or reflective capacity, of the earth. At the most, 14% is absorbed by the atmosphere. The remaining 43% or more is absorbed by the earth's surface. From this it can be calculated that the maximum theoretical solar radiation obtainable on the earth's surface is approximately 86% of 1.95 cal/min/sq. cm. or 1.68 cal/min/sq. cm. Observed values of the average local solar constant measured at various solar furnace installations in the United States are somewhat lower, varying from 1.5 cal/min/sq. cm. down to 0.9 cal/min/sq. cm. (6, Table II). This wide variation is not especially due to differences in latitudes or elevation but mainly to differences in the amount of water vapor and dust in the atmosphere.

The radiation which reaches the site of the solar furnace is composed of two components, direct radiation that can be concentrated with lenses and mirrors and diffused radiation that cannot be concentrated. The amount of the radiation which is diffused depends on the effects of gas molecules, dust particles and water vapor in the atmosphere. This diffusion varies with latitude, elevation, and weather. These effects are grouped together in the atmospheric transmission coefficient, η_a, and the actual radiation received at the site that can be concentrated, p_a, is $p_a = \eta_a p_o$ where p_o is the solar constant measured above the atmosphere (1.95 cal/min/sq. cm.).

Values of the direct radiation received here at Corvallis, Oregon were not found, however, it may be assumed that they fall within the range of the other solar furnaces in the United States. Taking an average figure of 1.25 cal/cm^2/min for p_o gives a value for η_a of about 0.65.

OPTICS DISCUSSION

The heat flux delivered to the target is dependent on two classes of optical factors, theoretical and operational. Under the theoretical classification are found the optical geometry variable of the concentrator;

1) Aperture, D
2) Ratio of aperture to focal length, D/f
3) Image diameter, d
4) Average heat flux at the image, p
5) Uniformity of flux distribution at the image
6) Efficiency at which the energy received by the concentrator is concentrated, E

The relationship between the diameter, d, of the sun image and the focal point, f, is

$$d = 2f \tan 16' = \frac{f}{107.3} \qquad (1)$$

$$d = \frac{26 \text{ in.}}{107.3} = 0.242 \text{ in.}$$

Sun image refers to the circular image formed on the focal plane by the part of the mirror at the axis.

The relationship between the aperture ratio, D/f, and the azimuthal or rim angle, θ, is

$$\frac{D}{f} = \frac{4 \sin \theta}{1+\cos \theta} = 4 \tan \frac{\theta}{2} \qquad (2)$$

where D = diameter of the paraboloid at the edge.

$$\frac{60}{26} = 2.31 = 4 \tan \frac{\theta}{2} \text{ and } \theta = 60^\circ$$

The power which is concentrated within the sun image is

$$P = \pi(\eta_a P_o) \quad f^2 \quad \sin^2 \theta \qquad (3)$$

$$P = 895 \text{ watts}$$

The heat flux per unit area in the sun image is

$$p = \frac{P}{\pi \left(\frac{d^2}{4}\right)} \qquad (4)$$

$$p = \frac{4 (\eta_a P_o) f^2 \sin^2 \theta}{d^2} \qquad (5)$$

$$p = C \ \eta_a P_o \qquad (6)$$

where C, the concentration ratio, is the ratio of the heat flux at the focal point of a solar furnace to the actual heat flux received from the sun by the receiver at normal incidence after reflection both per unit area, or,

$$C = \frac{p}{\eta_a P_o} \qquad (7)$$

also; $$C = \frac{4 f^2 \sin^2 \theta}{d^2} \qquad (8)$$

$$C = \frac{(4)\ (26)^2 \sin^2 \theta}{(0.242)^2} = 46.1 \times 10^3 \sin^2 \theta \qquad (9)$$

and $$p = 46.1 \times 10^3 \ \eta_a P_o \sin^2 \theta \qquad (10)$$

$$p = 720 \text{ cal/cm}^2\text{/sec}$$

DISCUSSION OF MATERIAL AND ACCURACY OF CONSTRUCTION

Under the operational classification are found those factors which reduce the performance of the furnace by the inefficiencies due to optical losses. These are: 1) Reflectivity loss of the reflectors, 2) Shadowing loss, 3) Geometrical imperfections.

Of the several alternatives for reflecting surfaces, namely, polished metals and front or back plated glass, back silvered glass is by far the more economical for plane reflectors and large parabolic concentrators. For smaller parabolic concentrators (up to maybe ten feet in diameter) polished metals are used. The corrosion problem associated with polished metals and front surfaced glass is readily overcome on back silvered glass by an electrodeposition of copper followed by a coating of varnish. Another disadvantage of polished metals is the difficulty in obtaining a nearly perfect plane surface for a reasonable cost. A good commercial grade of plate glass mirror is sufficiently planer up to about 20 inches square for a thickness of one-fourth inch (1, p.63). On the other hand polished metals are desirable for the smaller diameter parabolic reflectors due to the advantages over glass of strength and ease of construction to the desired parabolic form. In this case of these advantages are of more consequence than the detrimental effects of corrosion.

Once the materials of construction and the geometrical configuration are decided, the loss of reflectivity is fixed. The only factors which will alter this value of the reflectivity are dirty, scratched, or corroded reflectors. It is obvious that, to maintain the maximum transmission of radiant energy, care should be exercised when cleaning the reflectors and in their protection against weathering.

A value to represent the effect of the combined losses of reflectivity is designated η_r and is called the reflectivity efficiency factor. This value was estimated to be about 0.70 for the solar furnace constructed by Kennecott Copper Corporation (6, Table II). Due to the similarity between these furnaces it will be assumed that this value is essentially the same for the present furnace.

The shadowing loss is due to the non-reflecting portions of the reflectors or obstructions in the path of the sun's rays; the mountings, spaces between mirrors, the sample holder and bracket, the sun tracking device, and the temperature controlling device. Here again, to achieve the maximum transmission of radiant energy, it is desirable to keep these factors to a minimum.

Once the solar furnace is completed the shadowing loss will be constant barring any changes of the aforementioned factors. The shadowing loss factor is represented by η_s. This was estimated to be about 0.85 for the present furnace.

The geometrical perfection factor, γ, takes into account the deviation of the parabolic concentrator from a true paraboloid and the deviation of any plane reflecting surface from a true plane. For the geometrical configuration as used in the construction of the present solar furnace it was found by trial and error that this factor was by far the most critical and its very low apparent value, on the first adjustment of the mirrors, was due almost entirely to a lack of good planearity in both plane reflectors. If a value of 3/8 inch is taken as the actual diameter of the sun's image as obtained at the focus (this value was obtained on the last trial) and compared to the calculated value of 0.242 inches, then a geometrical perfection of approximately 65% is indicated. This compares very favorably with the values recorded (12, p.33), although somewhat larger in value.

The final equation which accounts for all of the factors to be considered in the design of a solar furnace is

$$p = 46.1 \times 10^3 \eta_r \eta_s \gamma \eta_a p_o \sin^2 \theta \qquad (11)$$

This equation may be revised by introducing an efficiency factor, E, which is equal to $\eta_r \eta_s \eta_a \gamma$. (12)

thus; $p = 46.1 \times 10^3 E p_o \sin^2 \theta$ (13)

Figure 9 graphically portrays the relationship between heat flux, p, efficiency, E, and rim angle, θ, for a parabolic concentrator (12, p.35).

A point that should be kept in mind is the sharp variation in heat flux with distance from the focal point. It has been shown (9, p.94-98) that moving above or below the true focal point by a distance equal to the diameter of the sun image will reduce the flux received to about 40%.

HEAT FLUX UTILIZED BY THE TARGET

The actual temperature which a target is able to attain is a function of the total heat input less the various heat losses. The difference between heat input and heat loss is known as the heat flux utilized by the target. Heat is lost by radiation, conduction, and convection which are related to the shape, size, and material of the target.

For the proper design of a solar furnace for

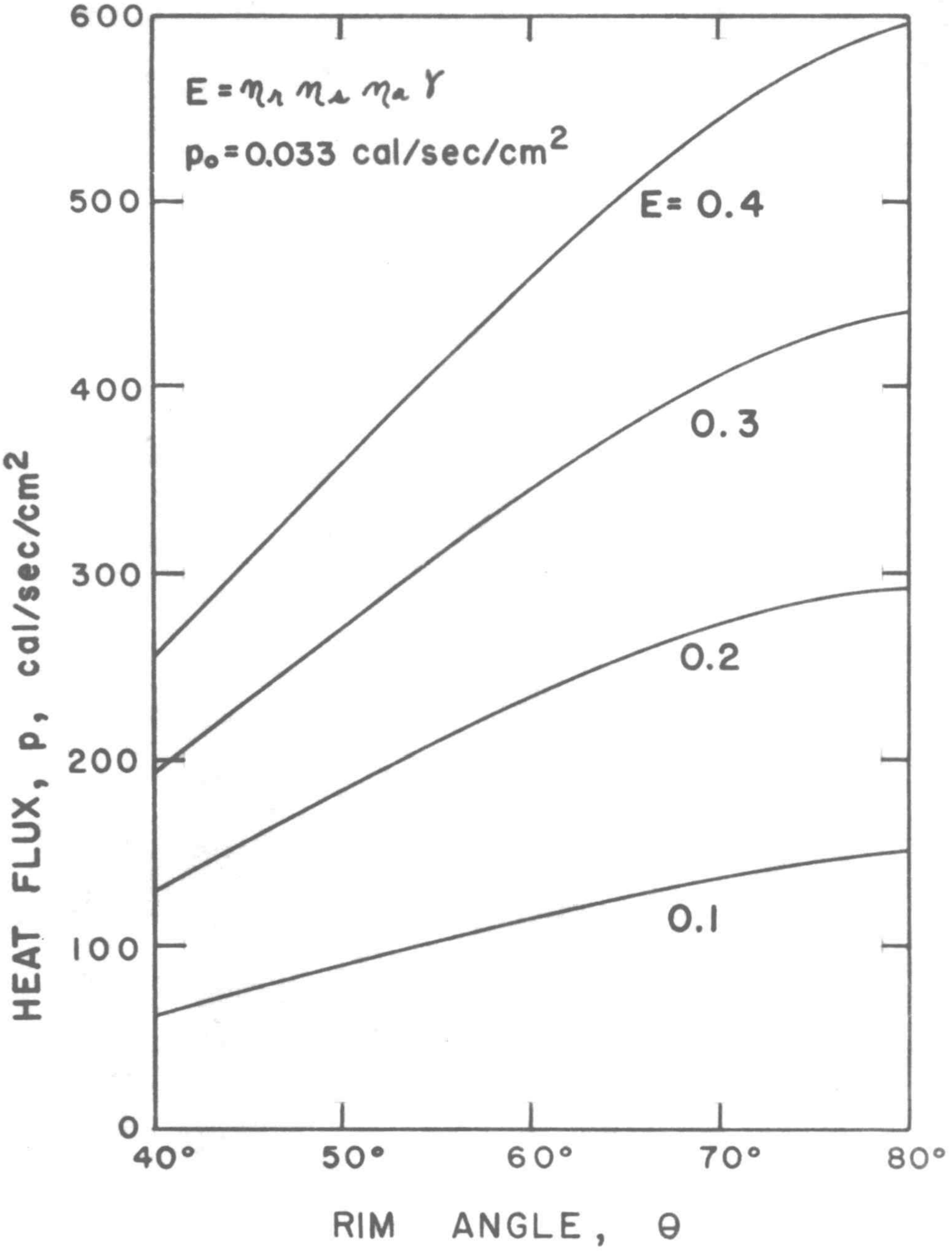

FIGURE 9 RELATIONSHIP BETWEEN HEAT FLUX, RIM ANGLE, AND EFFICIENCY FOR PARABOLIC CONCENTRATORS, (12, p. 35).

attaining a specified temperature, it is necessary to determine the heat flux required taking into account the heat losses. Also, the heat flux utilized by the target is of interest when knowledge of the theoretical and actual temperatures attainable is desirable.

The Stefan-Boltzman equation (12, p.33),

$$p = \sigma T^4 \qquad (14)$$

may be used to estimate the temperature obtainable with a solar furnace where:

σ = Stefan-Boltzman constant 1.355×10^{-12} cal/cm^2/sec°K

T = the temperature of the target, °K

p = $46.1 \times 10^3 \eta_r \eta_s \gamma \eta_a p_o \sin^2 \theta$ as calculated from the previously derived equation (11).

CONSTRUCTION OF THE SOLAR FURNACE

After becoming aware of the opportunity to purchase a surplus military searchlight, a preliminary investigation of the feasibility of constructing a solar furnace here at Oregon State College was made by a senior student, Ken Bird, under the supervision of Professor Joseph Schulein. The results of this investigation were encouraging so the searchlight was acquired.

Due to the desire to use the solar furnace for special research projects, it was decided that the most practical utilization of solar energy would be obtained if the sun's rays were concentrated downward which meant that the parabolic reflector would be mounted horizontally, i. e. with its axis vertical, and facing downward. With this configuration a stationary focus would be obtained on the top of the sample and the sample could serve as its own receptacle for experiments requiring melting. When the sample serves as its own receptacle the necessity of using very high temperature crucible is eliminated as is the possibility of introducing impurities.

The logical location was on the roof of the chemical engineering building, so, from a consideration of the site available, the five foot diameter parabolic reflector was mounted over a 45 degree stationary plane reflector which received reflected radiation from a heliostat. This arrangement is shown in Figure 4.

The geometrical configuration is shown in Figure 10 and is identical to that of the solar furnace constructed by Kennecott Copper Corporation in Salt Lake City, Utah. In the construction of that furnace difficulty was experienced in maintaining planeness of the mirrors on the heliostat and attributed it to flexing of the heliostat frame,of the mirrors,or both. Their mirrors were approximately 42 inches square. This flexing and the resulting improper alignment of the mirrors was indicated by tails in the focal image and by a change in shape of the focal image and movement of the tails from hour to hour.

The final design of the Oregon State College stationary plane and heliostat attempted to correct for planeness in the mirrors. The design was effected by another graduate student, Fred D. Fisher, and the construction was done by Fred D. Fisher and the author with advice from machinist Robert Mang on mechanical details. In the construction of the present furnace it was attempted to eliminate these defects by making the heliostat frame more rigid and by employing smaller mirrors measuring 21 inches square or one-fourth the

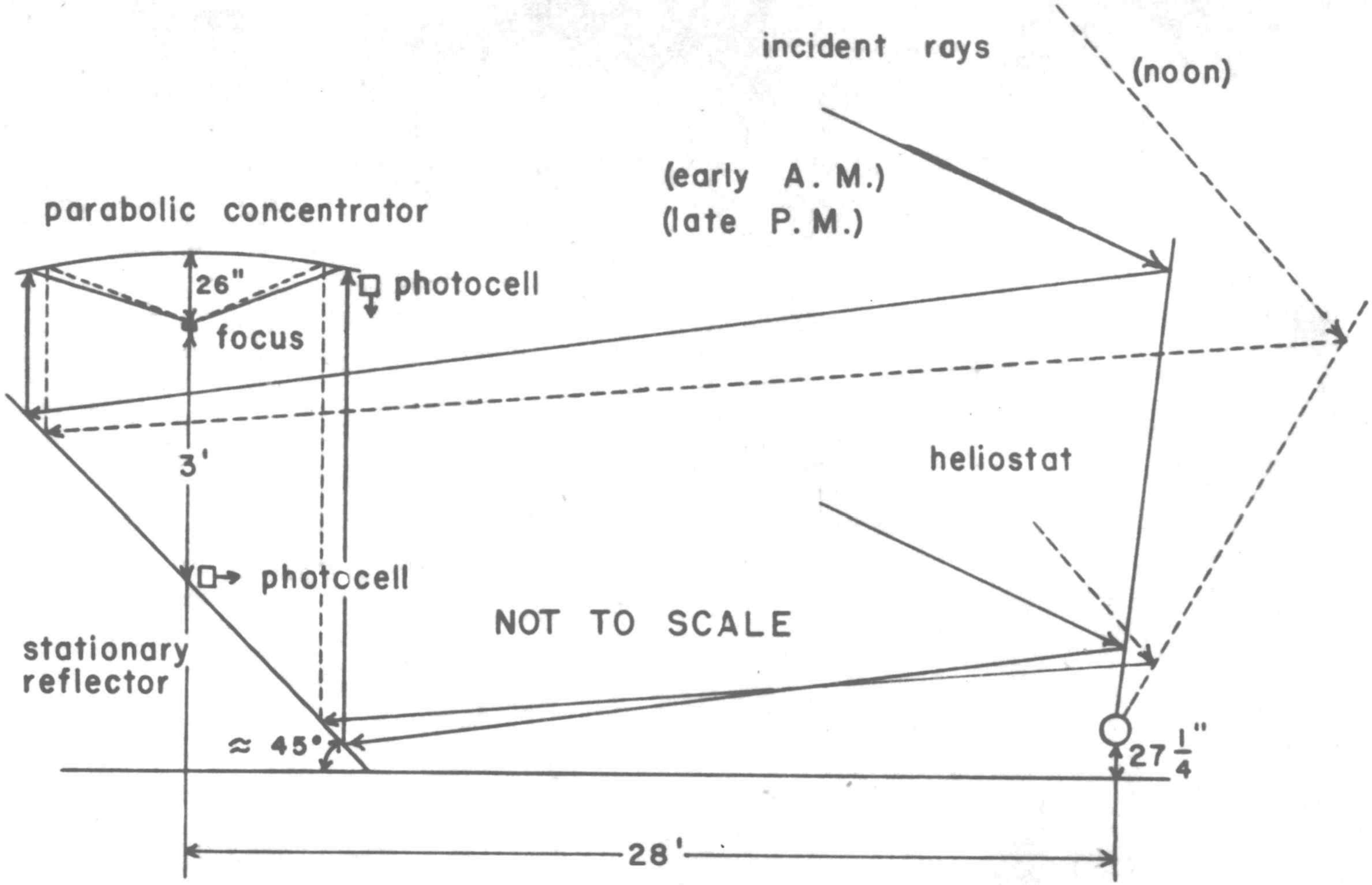

FIGURE 10 GEOMETRICAL CONFIGURATION OF THE OREGON STATE COLLEGE SOLAR FURNACE

size of those employed by Kennecott Copper Corporation.

CONCENTRATOR

The concentrator was, of course, the parabolic reflector from the surplus searchlight. The parabolic reflector was made by electrodeposition of copper on a mold and had a diameter of five feet with a focal length of 26 inches. The copper paraboloid was polished and plated with rhodium which has the necessary properties of corrosion resistance and reflectivity. The finished paraboloid was then mounted in an aluminum housing for protection and to support the stresses of mounting.

As shown in Figure 10, the concentrator was mounted with the focus about 3 feet above the midpoint of the 45 degree stationary reflector and on a separate frame. This distance provided sufficient clearance for working on the stationary mirrors and for the sample holder. The legs of the concentrator frame were made of 3½ inch steel pipe, the braces of 1¼ inch steel pipe and the top cross members of 4 inch steel I-beam. All parts were joined by welding. The concentrator frame is pictured in Figure 11.

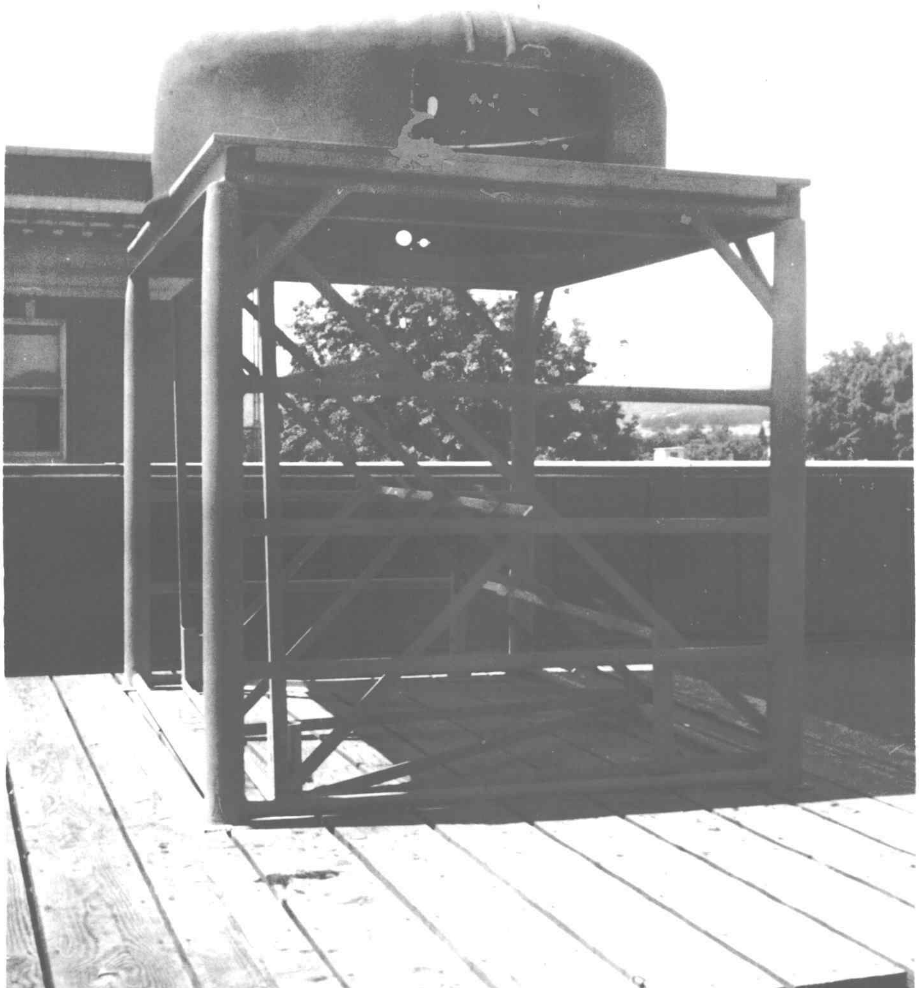

FIGURE 11 PARABOLIC CONCENTRATOR AND STATIONARY REFLECTOR FRAMES

STATIONARY REFLECTOR

The stationary reflector was welded up in the form of an inverted roof truss using 1½ inch steel angle iron. Concentric pipe sections were fashioned into legs for leveling the frame. This frame is shown in Figure 11.

From a consideration of the geometry of the installation it was ascertained that the heliostat should be seven feet square. This could be achieved by employing 16 mirrors 21 inches square. Both the stationary reflector and the heliostat were made the same size in order to use the same size mirrors.

Instead of the usual three point mirror mounting for this type of plane reflector it was decided to try a four point mounting in an attempt to decrease the stress at the mounting points and the resultant flexure of the mirror. Actually, it appeared during trials of the mirror adjustment that this four point mounting was not practical due to the impossibility of adjusting the four mounting points into the same plane and coinciding this plane into one single plane containing all the mirrors, or at least adjusting each mirror into very slightly offset parallel planes. This will be more fully discussed under "Adjustment of

Mirrors". Holes were drilled in the four corners of each mirror $1\frac{1}{2}$ inches from the side to receive $\frac{1}{4}$ inch stainless steel bolts. The location of the mounting holes in the mirrors fixed the location of the mounting pads which were welded on the frame where necessary.

HELIOSTAT

As mentioned previously, the frame of the heliostat was the same size as that of the stationary plane reflector except that on the heliostat the lower edge of the frame was cut off diagonally about 18 inches from the corners to allow space for mounting on the pivots. This is shown in Figure 12. The axis of the pivots passes approximately through the lower edge of the bottom row of mirrors. The supports for the pivots were made from 6 inch I-beam and were 6 inches tall. These supports were welded to the 6 inch I-beam cross member which was bolted to the modified searchlight carriage.

The base for the heliostat was made by slightly modifying the searchlight carriage. This modification consisted simply in cutting off one arm of the original searchlight yoke and cutting about six inches off the other arm. This remaining arm then served as the base for the elevating mechanism which was centered on the

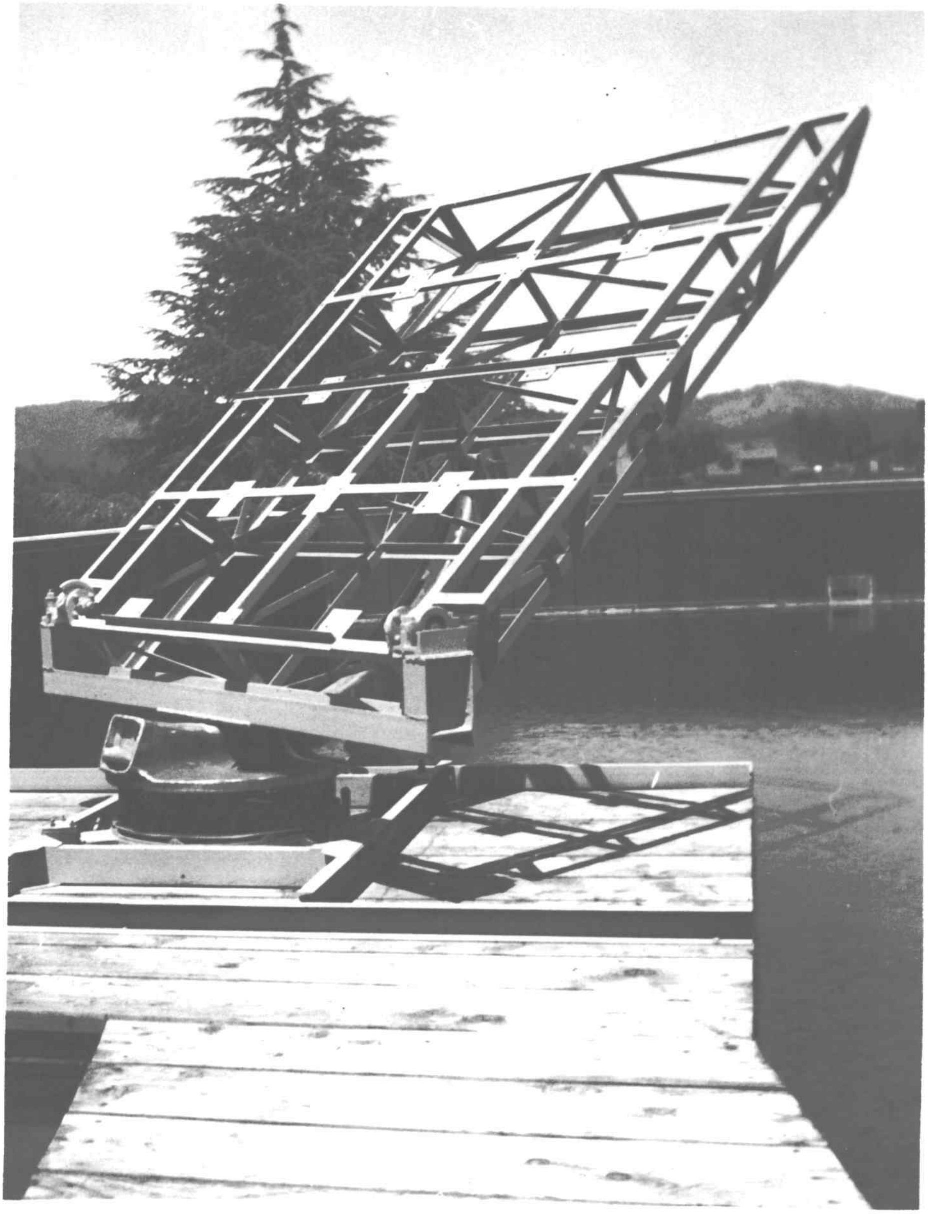

FIGURE 12 HELIOSTAT FRAME

back of the frame.

A one inch diameter bronze screw 46 inches long was fabricated and mounted in a special yoke at the rear midpoint of the heliostat frame. This yoke retained the screw and was mounted on bearings permitting vertical movement of the screw to allow constant alignment between both ends of the screw when raising or lowering the heliostat. The bottom end consisted of a similar arrangement except that a large nut was fabricated and mounted in the bearings. The bronze screw, turning through this fixed nut, raised or lowered the heliostat while being maintained in alignment by the bearing mounted supports at each end. Power was supplied by a ¼ horsepower reversible motor driving through reduction gears.

Movement in the horizontal or azimuthal plane was supplied by a 1/6 horsepower motor through reduction gears to the original traversing gear. A reversible motor was not needed here as the driving gear could be disengaged and the heliostat turned by hand.

The specific movement of the heliostat during the day while tracking the sun might be mentioned here to explain the choice of one reversible motor and one non-reversible motor. Starting in the morning the sun is low in the sky. Since the angle of incidence of the rays equals the angle of reflection of the rays the heliostat must be high to reflect to the stationary reflector. As the altitude of the sun increases the angle of incidence also increases, consequently, the heliostat must be lowered to increase the angle of reflection toward the stationary reflector. When the sun is at its zenith the heliostat is at its minimum point. As the sun goes down in the afternoon the heliostat must then move back up which is the converse of the procedure in the morning. From this it may be seen that the bronze elevating screw on the heliostat must work in two directions, screwing into the fixed nut in the morning and out in the afternoon. Two directions, hence a reversible motor. The heliostat, in tracking the sun, traverses steadily from east to west and the motor needs to function in one direction only since the heliostat can be easily turned back to the east by hand.

SUN TRACKING DEVICE

Two photocells were wired into the heliostat motors' circuits to control the movement of the heliostat. The window of each photocell was taped over leaving a very small slit. By this means the photocell could distinguish when the reflected rays from the sun were shining on it (see Figure 13). The normal operation of the photocell energized its exterior circuit upon seeing "dark", i. e. lack of radiation.

One photocell was mounted at the midpoint of the stationary reflector and controlled the horizontal movement of the heliostat. A black patch was placed at the midpoint of the heliostat (see Figure 14). This photocell was wired to actuate a normally open relay connected in the line to the heliostat traversing motor. While the photocell saw "light", the reflected radiation from the heliostat, the motor was "dead". As the sun traversed from east to west the shadow from the black patch would fall on the photocell, actuating it, closing the relay, and actuating the traversing motor. Once the heliostat had turned sufficiently for the photocell to see light it went "dead", thus opening the circuit of the motor and stopping it.

The other photocell was mounted facing down at the edge of the parabolic concentrator (see Figure 13). This photocell "saw" reflected radiation from the bottom edge of the stationary reflector, or the lack of reflected radiation. Connected to the exterior control circuit of the photocell was a normally closed relay which was wired into the circuit to the elevating motor. As the altitude of the sun increased in the morning the

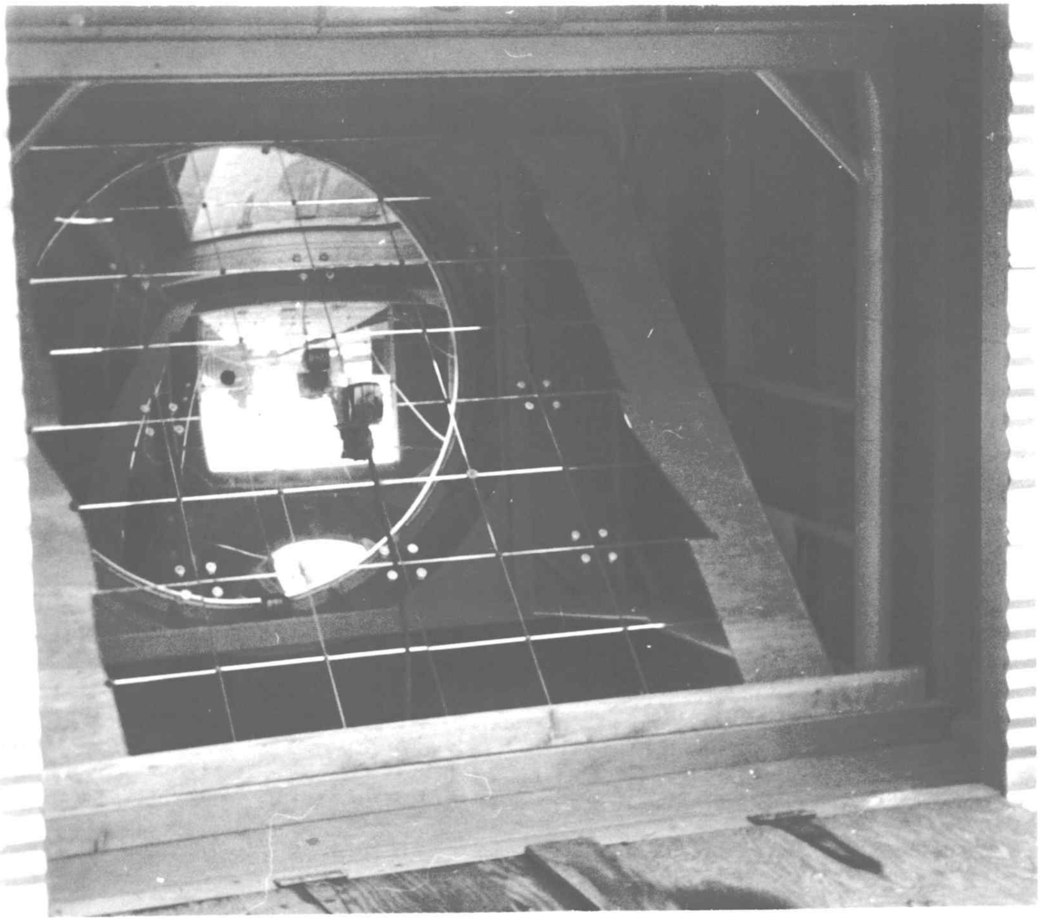

FIGURE 13   LOCATION OF PHOTOCELLS

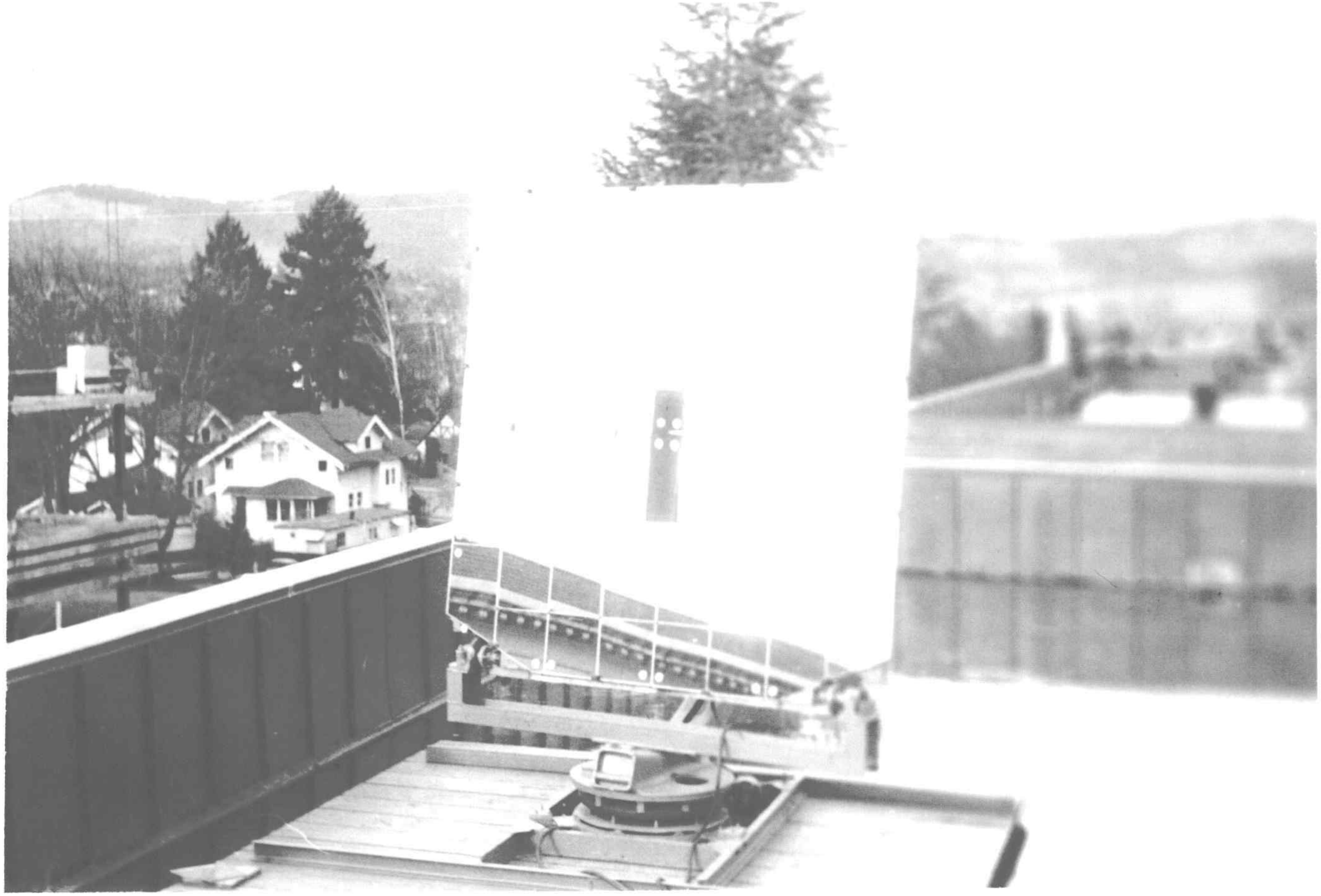

FIGURE 14 AZIMUTH CONTROL POINT ON HELIOSTAT

radiation would be reflected to the photocell, thus, in effect, keeping it de-energized. But, since the photocell was connected to a closed relay in the motor circuit, the motor would function, lowering the heliostat, until the photocell saw "dark". The photocell, being energized, would open the relay and stop the motor until radiation would again de-energize the photocell permitting the relay to close. In the afternoon the heliostat would have to be elevated. This was accomplished by laying out a separate circuit with switches and a normally open relay for reversing the process of energizing the elevating motor. The only manual operation of the tracking device came at the sun's zenith when the switches were thrown to reverse the movement of the heliostat. The switches were connected so that all were down when the heliostat was being lowered (morning operation) and up when being raised (afternoon operation).

SAMPLE HOLDER

Although the permanent sample holder was not completed, it will be briefly described. The original electrode mounting bracket was retained to serve as the mount for the sample holder. On this bracket will be mounted the base of the sample holder with provision for movement in any direction. Over the base will be fitted an inverted pyrex jar for maintaining the desired atmosphere around the sample. This pyrex jar will be sufficiently large so as to remain always in an area of slightly concentrated radiation. Fittings will be provided on the sample holder base for attaching vacuum and gas lines.

ADJUSTMENT OF THE MIRRORS

The most tedious portion, and the only portion requiring further modification, was the adjustment of the mirrors on both the heliostat and the stationary 45 degree reflector. It was very difficult to achieve a well defined circular focal image that would hold its shape for any length of time. This difficulty was also experienced by Kennecott Copper and Arizona State and probably by others.[1]

During the various stages of adjusting the mirrors a 6 inch square block of silicon carbide was clamped to two lengths of angle iron and positioned at the focal point of the concentrator. In this manner the size and shape of the sun image could be seen and the effect of each adjustment could be ascertained.

1. Personal communication from W. M. Tuddenham, Kennecott Copper Corporation, Salt Lake City, Utah.

FIRST STAGE OF ADJUSTMENT

In the first adjustment rubber shims were cemented on the frames at the mounting points to an approximate planeness as measured with a wooden straight-edge. The mirrors were placed in position and a final adjustment was effected by placing thin metal shims between the rubber pads and the mirrors. Linear image continuity was obtained across the joints but, as was discovered later, during the second stage of adjustment, there must also be an equality of image size across the joints. Referring to Figure 15, when mirrors AB and BC are co-planer the image as seen across joint B is the same size as when seen wholely in mirror AB or BC. When sides A and C are above B then the image as seen across the joint B will be elongated. When sides A and C are below joint B then the image as seen across B will be shortened. The net result is that a fairly good image linearity may be obtained rather easily but the mirrors cannot be considered in good adjustment until the image size is equal across the joints. This first adjustment gave a very diffuse focus with tails extending in all directions. In a test it took several seconds to char wood and a number of seconds to ignite wood. Shimming was continued with some improvement until it was possible to melt steel nuts (approximately 1500° C) but

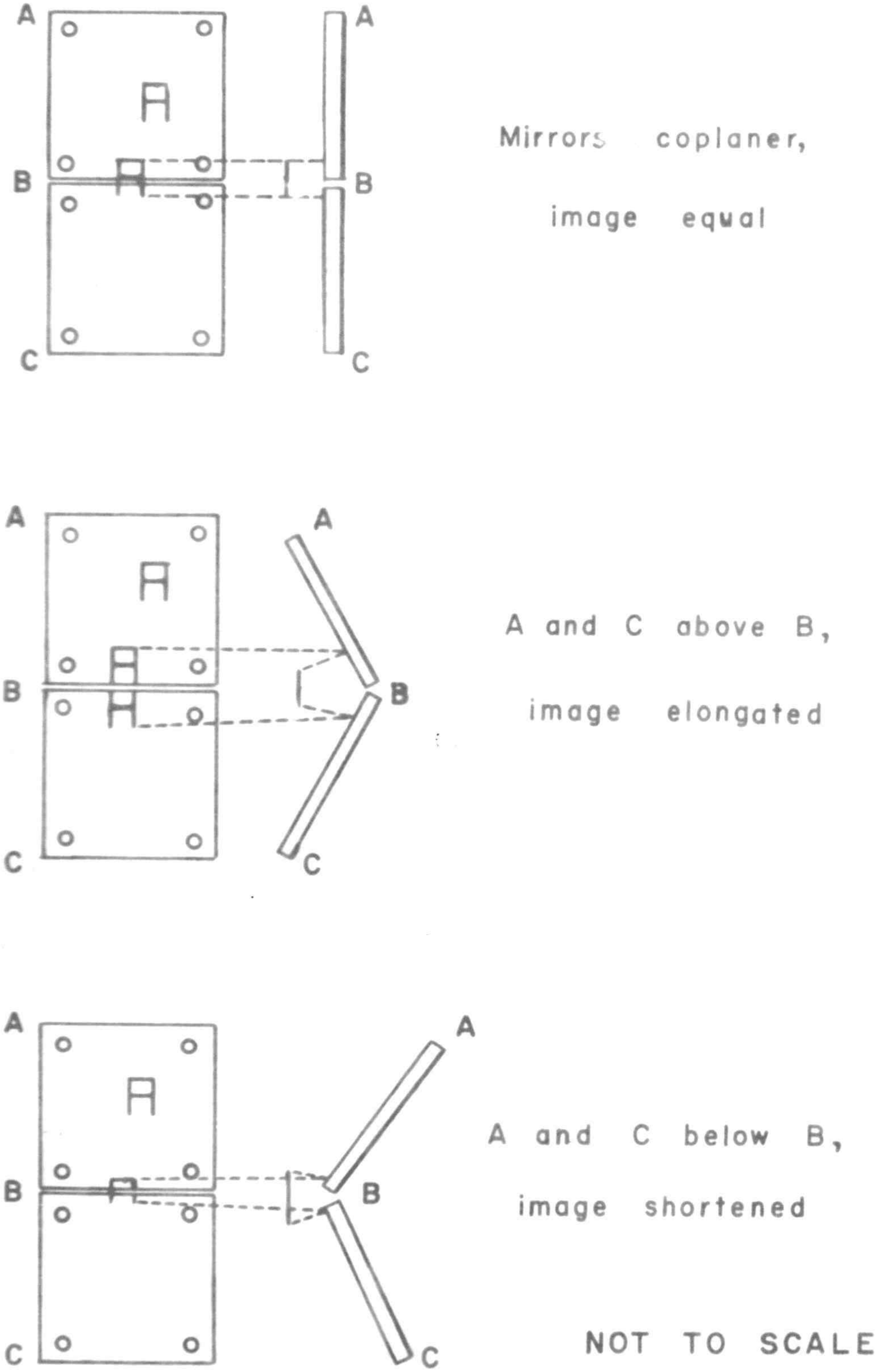

FIGURE 15 EFFECT OF NON-PLANENESS BETWEEN MIRRORS

the focus was still dispersed and with tails.

SECOND STAGE OF ADJUSTMENT

For the second adjustment the rubber pads were removed and three-fourths inch exterior grade plywood was placed directly on the frames and drilled to correspond to the mounting holes in the mirrors. The plywood was bolted to the frame with the mirror mounting bolts and shimmed behind to approximate planeness with the wooden straight-edge. Then the bolts for one mirror only were removed and the mirror bolted in place. This procedure was repeated for the rest of the mirrors in turn until both plane reflectors were completed.
It had been observed when testing the first adjustment that a slight pressure exerted in the center of many of the mirrors pulled the tails in toward the central focal point, so, for the second adjustment, corresponding holes in the plywood and center of the mirrors were drilled and all the mirrors were pulled down slightly in the center. This innovation was not very fruitful from an economical standpoint as several mirrors broke through the center. This adjustment gave a somewhat better focal spot, melting steel nuts rather readily, but there was still too much dispersion and too many tails at the focus. No improvement was achieved by

varying the tension of the mounting bolts or by adding or subtracting shims behind the plywood. At this point it was realized that an independent adjustment for each mirror must be provided in order to achieve the equality of image size across the joints which was explained in the first adjustment.

THIRD STAGE OF ADJUSTMENT

Since plywood was already cut to size and drilled for mounting on the frames it was decided to mount the plywood independently, level it to the best planeness achievable and then mount the mirrors with 1/16th inch soft rubber washers between the plywood and the mirrors. Wood screws and washers would be used on the corners without bolts. Thus, by varying the tension of the mirror mounting bolts and screws a slight adjustment could be made on any mirror. It was not known just how much, if any, the mirrors had sagged in the first adjustment due to their own weight and the method of mounting and then when breakage occurred after drilling holes in the centers of the mirrors it was decided to cut them into quarters. Actually, the smaller the mirror is the more nearly it resembles a perfect plane and that is just where the difficulty lay, an inability to achieve a nearly perfect plane reflector. Needless to say the mounting problem was magnified with four times as many mirrors, however, the equality of image size across the joints could then be ascertained at points only one-half as far apart as previously. This would aid the construction of a more nearly perfect plane reflecting surface.

Flathead bolts were counter-sunk into the plywood to affix the plywood, independently of the mirrors, to the frames. The plywood was then shimmed out to approximate planeness and a manual sander was then made for leveling off the high spots on the plywood. A three foot steel straight-edge had been acquired and was used to ascertain that a variance of no more than about ten-thousandths of an inch was achieved. The mirrors were then mounted as explained previously. Although the plywood had been varnished it was found, when mounting the mirrors, that the variation between high and low spots was increasing with time, so thin shims also had to be used in some places. A good continuity of image size was obtained across the joints and the furnace was tested after one-half of the mirrors had been mounted on the heliostat and the stationary reflector. The results of this test are amplified in the section "Test of the Solar Furnace". By the time the rest of the mirrors had been mounted, the plywood had warped sufficiently so that a dispersed focal image was again obtained. It was realized before employing the plywood that it did not have the desired resistance to weathering but it was thought that a test of some significance could be obtained if the mirrors could once be properly adjusted, even if only for a few days. The method of shimming behind the mirrors was too tedious to make any further adjustment of the mirrors desirable. This change in the focal image with a slight change in the adjustment of the mirrors emphasizes just how critical the mirror adjustment is and the fact that mounting devices must be impervious to weathering.

TEST OF THE SOLAR FURNACE

As the adjustment of the mirrors improved, the temperature at the focal point increased from about the kindling point of wood to the melting point of steel (± 1500°C) and somewhat beyond. A more accurate determination of the temperature was not considered because it was seen that the focal point was still not well defined, however, it was attempted to melt boron under a vacuum (m.p. at 1 atm. is 2050° C). A 3 liter florence flask was fitted to hold a small piece of boron and receive a vacuum line. The boron got red hot but did not appear to melt.

The only high temperature test of any consequence was obtained on October 14, 1958 at about 12 noon. One-half of the mirrors had been mounted on the plywood on both the stationary reflector and the heliostat and were in very good adjustment as was corroborated by the symetry and definition of the image. The day was only fairly clear, there being sufficient haze to partially obscure the medium distant hills. The mirrors had been cleaned previously but were dusty.

A well-defined image of approximately 3/8 inch in diameter was observed. A steel shim was placed in the focus and the resulting hole which was burned measured slightly less than 3/8 inch in diameter and was of a very well-defined circular shape. Pyrometric cones were placed in the focus to estimate the temperature. Cone # 33 representing 1745 degrees C. was fused several times and was the highest indicated temperature obtained under the aforementioned test conditions.

This test was very encouraging inasmuch as it was the first time that a well-defined focal spot, without tails, was obtained.

After mounting the rest of the mirrors it was observed that warpage and grain swelling of the plywood had caused a dispersion at the focal point. Pyrometric cones indicated a temperature of only 1820° C.

INTERPRETATION OF TEST RESULTS

From the calculations demonstrated in the Appendix and using the results of the test run involving only one-half of the mirrors and making the following assumptions and estimates, an estimated operating temperature for the completed solar furnace will be determined.

Referring to the formula for the efficiency, E,

$$E = \eta_r \eta_s \gamma \eta_a \qquad (12)$$

corrected values will be substituted to estimate the temperature obtainable about the time of the June solstice (June 21).

η_r = the combined reflectivity coefficient of all the reflecting surfaces, both sets of mirrors and the parabolic concentrator. This will be the same as the test run.

η_s = the shadowing coefficient which accounts for the non-reflecting portions of the reflectors due to mounting, spaces between mirrors, sample holder and bracket, and sun tracking device. This will be slightly less due to the sample holder, say 90%.

γ = the coefficient of geometrical perfection. This will be the same providing the mirrors are as well adjusted as in the test.

η_a = the coefficient of transmission of the atmosphere. This will be much greater due to clean reflectors, clearer atmosphere,[2] and the higher elevation of the sun.

Due to lack of data on the direct radiation of the sun for this general geographical area, an estimate will have to be made for this most important factor. The author feels that it may be conservatively estimated that at least twice the intensity of direct radiation will be received by the solar furnace around June 21 on a clear day as during the October 14 test. This estimate is purely personal judgment and tries to take into account the difference of dust and water vapor in the atmosphere, clean reflectors, and the higher elevation of the sun.

Since only one-half of the mirrors were used as well as approximately one-half of the parabolic concentrator, then the intensity will be approximately doubled with the utilization of all of the mirrors.

2. During the summer of 1958, the atmosphere appeared quite clear until the latter part of July and later when a constant haze was evident. This haze was estimated to be of approximately the same intensity as during the test.

An equation for estimating the change of efficiency to be expected at any other time would be:

$$E' = \eta'_r \eta'_s \gamma' \eta'_a \text{ (area intercepting radiation)}$$

where the primes, ', represent the estimated changes of the values.

$$E' = (1)\ (0.90)\ (1)\ (2)\ (2) = 3.6$$

From the Stefan-Boltzman equation, $p = \sigma T^4$, and equation (11), $p = 46.1 \times 10^3 \eta_r \eta_s \gamma \eta_a p_o \sin^2 \theta$, it is seen that this factor E' taken to the one-fourth power will be the correction coefficient by which the temperature must be multiplied.

$$\sqrt[4]{3.60} = 1.38$$

$$(1.38)\ (1745 + 273) = 2780^\circ \text{ K}$$

or approximately 2500° C.

This value is the estimated temperature which the solar furnace should reach on a clear day in June, based on the results of the test run involving one-half of the mirrors.

This extrapolated temperature appears to be very conservative when it is remembered that the Kennecott Copper Corporation in Salt Lake City, Utah, with a solar furnace of identical geometrical configuration obtained 2800 degrees C without achieving a perfect focus.

As an item of interest, extrapolating for all the mirrors and calculating an expected temperature for October 14, one finds;

$$E' = (1)\ (0.90)\ (1)\ (1)\ (2) = 1.8$$

$$\sqrt[4]{1.8} = 1.185$$

$$(1.185)\ (1745 + 273) = 2390^\circ\ K$$

$$\text{or } 2117^\circ\ C.$$

CONCLUSIONS

While there was some pessimism concerning the feasibility of a solar furnace in this geographical location both before construction was commenced and particularly when attempting to adjust the mirrors it must now be concluded that an operable solar furnace is very feasible for summer operation.

A point that cannot be overly stressed is the necessity for good optical alignment of the mirrors. It was discovered that this point, more than any other, was the real key for obtaining high temperatures.

Since the solar furnace was originally constructed to attempt zone refining of elemental boron which melts at 2050° C and a driving force of several hundred degrees is probably necessary , then, temperatures of probably 2400° C or higher are desirable. Consequently, for work in this temperature range, the solar furnace would appear to have utilizable maximum period of use of less than six months and more probably about four months from approximately April 21 to August 21.

RECOMMENDATIONS

It is recommended that the mirrors be remounted on springs with a provision for front adjustment. Three point suspension is preferable to four point because the same accuracy of alignment can be achieved with one less point of adjustment and there is less possibility of producing undesirable stresses in the mirrors. Figure 16 shows the additional holes necessary in the mirrors and indicates two suggestions for spring mounting the mirrors.

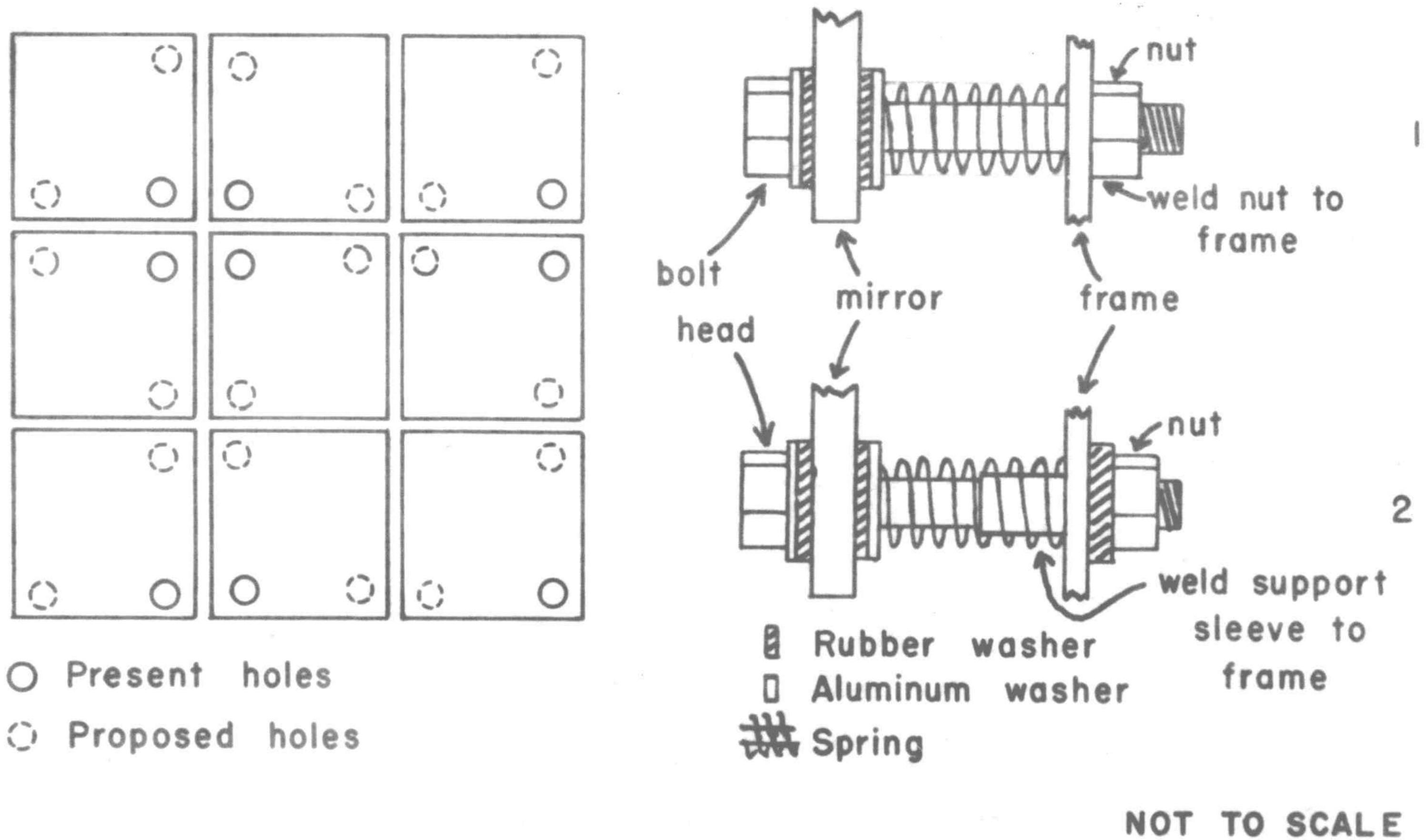

FIGURE 16 PROPOSED MIRROR MOUNTING

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A P P E N D I X

SUMMARY OF CALCULATIONS FOR THE O.S.C. SOLAR FURNACE

(1) $$d = 2f \tan 16' = \frac{f}{107.3}$$

$$d = \frac{26 \text{ in}}{107.3} = 0.242 \text{ in.}$$

(2) $$\frac{D}{f} = \frac{4 \sin\theta}{1+\cos\theta} = 4 \tan\frac{\theta}{2}$$

$$\frac{D}{f} = \frac{60 \text{ in.}}{26 \text{ in.}} = 2.31 = 4 \tan\frac{\theta}{2}$$

$$\theta = 60^\circ$$

(3) $$P = \pi\, (\eta_a\, P_o)\, f^2 \sin^2\theta$$

$(\eta_a P_o)$ will be taken as 1.25 cal/cm^2/min which is approximately the average from other solar furnaces in the United States.

$$P = (3.1416)\,(1.25)\,(26^2)\,(\sin^2 60^\circ)\,(\text{conversion factor})$$

P = 716 watts which is the total

power, or heat flux, concentrated in the sun image at the focal point.

(9) $p = 46.1 \times 10^3 \eta a p_o \sin^2 \theta$

$p = 720$ cal/cm^2/sec which is the maximum theoretically obtainable heat flux per unit area at the focus.

(10) $p = 46.1 \times 10^3 \eta_r \eta_s \gamma \eta_a p_o \sin^2 \theta$

η_r, the reflectivity efficiency factor, will be taken as 0.70 which is the value estimated by Kennecott Copper Corporation for an identical furnace. Values for other furnaces varied from 0.66 to 0.86 (6, Table II).

η_s, the shadowing loss factor, varied from 0.63 to 0.964 (6, Table II) with the majority 0.95 or higher. It was felt that the value for the present solar furnace should be lower than for other similar furnaces due to the smaller mirrors, their mounting, the sample holder and mounting, and the tracking device. Therefore a value of 0.85 will be assumed.

γ, the geometric perfection factor, has been conservatively calculated (12, p.33) for several furnaces and was found to vary from 0.066 to 0.54. These are conservative values inasmuch as no shadowing loss was assumed in making the calculations. Approximating the shadowing loss and recalculating gave maximum values of about 0.60. It will be remembered that a calculation for the present furnace based on the test with one-half of the mirrors indicated a geometric perfection of about 0.65. γ, then, will be conservatively estimated as 0.50 for the present calculation.

$\eta_a P_o$, the local solar constant, was found to average approximately 1.25 cal/cm^2/min (6, Table II). While it is felt that this value should be surpassed, especially about the time of the June solstice, it will nevertheless be assumed as a lower value to continue the presentation of a conservative estimate of the heat flux obtainable for the present furnace. Assume this factor is 1.0 cal/cm^2/min.

$p = (46.1 \times 10^3)\ (0.70)\ (0.85)\ (0.50)\ (1.0)\ (\sin^2 60^\circ)$

$p = 10300$ cal/cm^2/min $= 172$ cal/cm^2/sec

The various loss factors may be represented by

(12) $E = \eta_r\ \eta_s\ \eta_a\ \gamma$

By using the Stefan Boltzman equation

(14) $p = \sigma\ T^4$

The temperature which the solar furnace is estimated to attain is 3360° K or 3087° C.

The results of the calculations indicate that the present furnace will attain temperatures corresponding to those of other furnaces.

It will be of interest to see what effect variations in the loss factors, η_r, η_s, η_a, and γ have on the obtainable temperature. For this purpose Figure 9 will be used.

The rim angle for the present furnace is 60°. Heat flux, p, will be calculated from the Stefan-Boltzman equation by assuming temperatures. E will then be read from Figure 9 and factored to give representative values for each loss factor component. Since values of the atmospheric loss factor, η_a, are not as readily available as the local solar constant, $\eta_a p_o$, the local solar constant value will be included for a comparison. These results are given in Table 2.

From these calculations it can be seen that the efficiency may be as low as 0.062 and still allow the achievement of approximately 2400° C which was considered as about the lowest desirable temperature for melting boron.

TABLE 2

SEVERAL RELATIONSHIPS BETWEEN THE LOSS FACTORS AND TEMPERATURE

T, °C	p, $\frac{cal}{cm^2\ min}$	E	η_r	η_s	η_a	γ	$\eta_a p_o$
2200	50.4	0.045	0.60	0.59	0.361	0.35	0.7
2400	68.7	0.067	0.63	0.60	0.412	0.40	0.8
2500	80.0	0.070	0.65	0.58	0.412	0.45	0.8
2700	105	0.090	0.65	0.64	0.464	0.47	0.9
2800	120	0.105	0.70	0.69	0.464	0.50	0.9
2900	136	0.120	0.70	0.67	0.515	0.50	1.0
3000	155	0.130	0.70	0.72	0.515	0.50	1.0
3087	172	0.150	0.70	0.85	0.515	0.50	1.0
3200	196	0.170	0.70	0.85	0.567	0.50	1.1
3300	219	0.190	0.70	0.80	0.618	0.55	1.2
3400	245	0.215	0.70	0.84	0.67	0.55	1.3
3500	272	0.250	0.70	0.83	0.722	0.60	1.4