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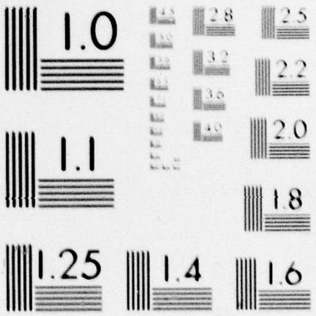
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Technical Note

CEL

TN no. N-1556

title: SOLAR-POWERED SUN TRACKER

author: Carter J. Ward, Ph D

date: June 1979

sponsor: Naval Material Command

program nos: ZF57.571.01.01.010

CIVIL ENGINEERING LABORATORY
NAVAL CONSTRUCTION BATTALION CENTER
Port Hueneme, California 93043

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER (14) CEL-TN-1556	2. GOVT ACCESSION NO. DN687065	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) SOLAR-POWERED SUN TRACKER.		5. TYPE OF REPORT & PERIOD COVERED (9) Final rept. Feb [redacted]77 – Sep [redacted]79,
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) Carter J. Ward Ph D		8. CONTRACT OR GRANT NUMBER(s) ∅
9. PERFORMING ORGANIZATION NAME AND ADDRESS CIVIL ENGINEERING LABORATORY Naval Construction Battalion Center Port Hueneme, California 93043		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62765N; (17) ZF57571 01[redacted]
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Material Command Washington, D.C. 20360		12. REPORT DATE (11) Jun[redacted]79
		13. NUMBER OF PAGES 29
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) (12) 33		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited. (16) F57571		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report) (17) ZF57571 [illegible]		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Solar energy, solar tracker, passive solar controls.		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A solar-powered sun tracker believed to be capable of repositioning equipment to within 1 degree of the angle-of-incident radiation is described in this report. The proposed tracker is designed to reposition itself automatically after cloudy periods and should prove inexpensive as well as reliable. Included in this report are (1) a description of two tracker concepts, (2) a derivation of the heat-balance equation used to predict work available for equipment rotation, (3) a discussion of the experimental model fabricated to prove concept feasibility, (continued)		

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and (4) an economic analysis comparing the cost of generating steam with a solar-powered boiler with the cost of generating steam with a coal-fired boiler.

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Civil Engineering Laboratory
SOLAR-POWERED SUN TRACKER (Final), by
Carter J. Ward, Ph D
TN-1556   29 pp illus   June 1979   Unclassified

1. Solar energy   2. Solar tracker   I. ZF57.571.01.01.010

A solar-powered sun tracker believed to be capable of repositioning equipment to within 1 degree of the angle-of-incident radiation is described in this report. The proposed tracker is designed to reposition itself automatically after cloudy periods and should prove inexpensive as well as reliable. Included in this report are (1) a description of two tracker concepts, (2) a derivation of the heat-balance equation used to predict work available for equipment rotation, (3) a discussion of the experimental model fabricated to prove concept feasibility, and (4) an economic analysis comparing the cost of generating steam with a solar-powered boiler with the cost of generating steam with a coal-fired boiler.

CONTENTS

INTRODUCTION

This document is a summary report on the initial development of a solar-powered sun tracker. Although no working model has been produced to date, this report presents a concept that is believed capable of being used as the basis for an inexpensive, reliable, accurate, and energy-efficient tracking system. This document outlines some of the simplified approaches for designing this sun tracker and describes its working principles.

Sun tracking systems capable of accurately repositioning sun tracking equipment (such as concentrating solar collectors) are needed to power solar refrigerators, air conditioners, and cooking systems requiring fluids with temperatures in excess of 200°F. Flat-plate collectors commonly used for space heating and domestic hot water are not currently capable of economically producing temperatures this high. As a result, concentrating collectors are needed; however, one disadvantage of these devices is the necessity of accurately maintaining the reflective surface perpendicular to the incident radiation. Of equal importance is the need for tracking systems to drive the large quantity of individual flat-plate solar reflectors necessary to power the large electrical solar generator plants.

BACKGROUND

Current tracking systems employ one of three basic techniques for repositioning:

(1) Computerized position control, repositioning the reflector as a function of time by using previously recorded solar angular positions as reference for a two-axis system or a 24-hour clock mechanism for a single-axis system

(2) Solar cell with electrical feedback for position control

(3) Fluid mechanical or bimetallic solar-heat-powered position control

Computerized control requires a very accurate electrical feedback system located at the reflector to ensure that repositioning is precise. This type of equipment is delicate and, as a result, is difficult to maintain in an outdoor environment. Additionally, direct mechanical drives, such as worm gear actuators, are required to handle high wind loads. Consequently, viscous damping systems often used for retarding rapid position movements are not applicable because direct-drive mechanisms do not permit any displacement. Similar logic would also apply to clock mechanisms. Solar cell systems could use a spring damper linkage in the actuator control because the feedback control need not be directly attached to the frame, but the electrical equipment would be just as difficult to maintain in the outdoor environment as the computerized system and clock mechanism.

Solar-heat-powered control systems do not require any electrical power input to operate. Such devices are expected to be trouble free and easy to maintain because the hardware is simple and all mechanical. Essentially, the sensor acts as a shade-seeking device in that the mechanism seeks a position where the sensor, when partially shaded, balances its driving forces actuated by either fluid pressure or bimetallic expansion. To date, only one known solar-powered tracking device has been tested. This device, developed by E. A. Farber et al. at the University of Florida, proved to be workable (Ref 1). However, tests demonstrated that the system was only accurate to within an average deviation of 4.86 degrees, which is not accurate enough to generate the high-temperature fluids necessary for a trough-type solar collector. The device also responds slowly to the morning sun.

The Farber system utilizes two sensor bulbs connected to power cylinders configured to oppose each other through a rack-and-pinion gear arrangement, as shown in Figure 1. Pressure differentials, created by unequal shading of the sensor bulbs, drive the cylinders, which rotate the parabolic trough into a position normal to the sun's rays. Refrigerant 12 was used for the bulb working fluid. Figure 2 shows an end view of the Farber tracking system. Included in the figure is a derivation for the differential solar energy input created by the unequal shading. It is important to note that the repositioning solar energy is a sinusoidal function of the angle between the solar incident rays and the axis of the trough's concave reflector. For a trough solar collector to work properly, its reflected solar rays must focus to a focus line that lies directly on the collector tube used for heating the high-temperature fluid. If the solar incident rays are angled slightly relative to the reflector's axis by an angle θ, the focus line will be positioned at a distance of $(f) \sin \theta$ away from the centerline of the collector tube.* For example, a parabolic trough having a width of 5 feet could be expected to have a focal length of 2 feet and a collector tube 1 inch in diameter. Such a collector could not tolerate a position angle error of more than 1.2 degrees; otherwise the collector tube would be placed outside the focus line. As a result, a position accuracy requirement of 1 degree is not unrealistic for a trough-type collector.

The heat-balance equation used to predict how much work is available to rotate the Farber reflector is:

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*The term f is the focal length of the trough's reflector.

$$\frac{W}{J} \cong Q - C_{p_c} W_c \Delta T - C_{p_b} W_b \Delta T - \Delta h_f W_f - h_{fg} W_{fg} - \Delta h_g W_g - h_c A \Delta T \Delta t \qquad (1)$$

where W = work available to rotate device, ft-lb (Nm)

J = mechanical equivalent of heat 778 ft-lb/Btu (1 Nm/joule)

Q = differential solar energy input to the sensor tubes, Btu (joule)

C_{p_c} = specific heat of the cylinders and piston material, Btu/lb-°F (joule/kg °K)

W_c = weight of the cylinders and pistons in contact with the working fluid, lb (kg)

ΔT = average change of temperature of the complete system including sensor tube, cylinders, pistons, and working fluid, °F (°C)

C_{p_b} = specific heat of sensor tube material, Btu/lb-°F (joule/kg °K)

W_b = weight of sensor tubes, lb (kg)

Δh_f = change in enthalpy of working fluid, Btu/lb (joule/kg)

W_f = weight of working fluid, lb (kg)

h_{fg} = heat of vaporization of the working fluid, Btu/lb (joule/kg)

W_{fg} = weight of working fluid evaporated, lb (kg)

Δh_g = change of enthalpy of working fluid in gas phase, Btu/lb (joule/kg)

W_g = weight of working fluid in gas phase, lb (kg)

h_c = system's average heat-loss convection coefficient, Btu/hr-sq ft-°F (watts/sq m °K)

A = system's equivalent exposure area to heat loss, sq ft (sq m)

Δt = time period of analysis, hr

Equation 1 may be simplified to:

$$\frac{W}{J} = Q - Q_{loss} - C_p W \Delta T \qquad (2)$$

where Q_{loss} = energy lost through convection, Btu (joules)

$C_p W \Delta T$ = equivalent heat absorbed into the system, Btu (joules)

If the trough collector is balanced and the differential solar energy input derived in Figure 2 is substituted for Q, Equation 2 becomes:

$$\frac{1}{J}(W + T_\mu \beta) = 2 \varepsilon \sigma L Ft(T_s^4 - T_b^4) \sin \theta$$

$$- (Q_{loss} + C_p W \Delta T) \qquad (3)$$

where T_μ is the resisting frictional torque of the trough and β is the required angle the trough must rotate in the Δt time period to track the sun's movement. The emissivity ε is a function of the surface material, and σ is the Stefan-Boltzmann universal constant for black-body radiation.

Equation 3 was derived to illustrate the performance of the Farber tracking system for the reader, who can then better comprehend how various improvements might affect the system. For example, if an accuracy of 1 degree is required, the sinusoidal function ranges between 0 for perfect alignment to only 0.017 for an error of 1 degree. The solar energy available to rotate the trough would greatly increase if the sinusoidal function was replaced by a larger gain factor of higher sensitivity. Unfortunately, the Farber tracker design is configured so that if the solar sensor tubes are increased in length and radius to improve the input energy sensitivity, the additional mass of the tubes would require more energy to heat the system for the same ΔT. Consequently, little would probably be gained by increasing the sensor surface areas.

DISCUSSION

A schematic of the proposed solar tracking concept is shown in Figures 3 and 4. The drive mechanism consists of a four-bar linkage powered by two expansion bellows, which are encased in cylinders to reduce convection heat transfer and to eliminate buckling. The bellows facing east is used to compensate the environmental temperature effects. The west-facing bellows is plumbed into the sensor so that the vapor pressure increases derived from the sensor temperature rise will rotate the parabolic trough westward. This system does not include gears or high-friction sliding devices such as those found in rack-and-pinion drive and cylindrical actuators. The bellows' fluid-drive system is completely enclosed to protect the working fluid from contamination and loss. The bellows spring forces - plus the nighttime cooling of the sensor bulb - will reposition the trough to face east in the morning. Consequently, this tracking system should have a good morning response because little sunlight energy is required for early repositioning. Like the Farber device, only small displacements are required to follow the sun's movement (i.e., 1 degree every 4 minutes). It is important to note that the proposed system uses only one rotational sensor heating element to drive the system in one direction against a spring force. This approach is recommended to improve the morning response and reduce the cost of the sensor. However, two parallel-plate-type sensors could be just as easily used to pressurize the drives for both bellows similar to the Farber system. The resulting system should prove to be more accurate because the parallel-plate system has a larger solar gain at the small error angles.

Although the one experimental model fabricated to date did not work, high accuracy is still expected with a developed, parallel-plate, solar filter system. In addition to the high rotational friction torque inherent with the Farber system, the three main causes for its inaccuracy are attributed to (1) the small solar gain factor, sin θ; (2) the large thermal mass of the working fluid system; and (3) its large exposed external convection area.

Figures 4 and 5 illustrate two concepts for improving the sensor elements. The parallel-plate type shown in Figure 4 has the advantage of high accuracy control over the solar incident energy input as a function of error angle. The plates may easily be dimensioned to acquire a large variation of Q input for small solar-angle changes. The disadvantage of the parallel-plate scheme is that for cases where clouds (which tend to position the tracker behind the angle of the sun) are encountered, the solar energy input to the sensor bulb via the solar reflector (positioned below) is limited. It could require excessive time to heat the bulb enough for the trough to catch up. The alternative concept shown in Figure 5, however, proposes a type that should be able to reposition the trough quickly and properly when the sun comes out from behind clouds. Point A of Figure 5 is the sensor tube, and attached to it is a thin fin which extends to point B. The tube and fin lie in the focal plane of the fresnel lens so that, for solar angles equal to or greater* than that at which the solar incident is parallel to the trough reflector axis, concentrated solar energy impinges the sensor bulb or fin. Figure 6 illustrates what is believed to be the relationship of the differential solar energy inputs available to drive the parabolic trough reflector as a function of the error angle between the solar incident rays and the trough reflector axis for the Farber unequal shading sensor and the two tracking types presented in this report. The dip in the curve of the parallel-plate sensor for positive angles of θ is due to the change in the sensor's source of solar energy. The rapid fall is caused by the increased shading of the parallel plates; and the gradual rise is caused by the increasing reflective energy from the curved concentrating reflector positioned below the sensor bulb. The low point position is a function of the width of the sensor's reflector shade (see Figure 4). The gradual temperature decrease of the fresnel lens sensor for positive angles θ is due to the convective heat loss of the fin. The large decrease is due to large solar-angle errors where the rays are focused beyond the fin end point (i.e., point B).

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*For angles no larger than those in which the rays are focused at the end of the fin at point B.

Another advantage of the two concepts presented here over the Farber tracker system is that the latter system's thermal mass (which includes the working fluid, sensor bulb, and actuators) can be greatly reduced because concentrating lenses are used in the sensors. As a result, if more input solar energy is required, the lenses can simply be increased in size without increasing the sensor bulb mass. The bellows actuators can also be lightweight. Also, because the sensor bulbs are small, they can easily be insulated inside glass tubes so that wind effects are held to a minimum, which also decreases the convection losses.

Experimental Model

The parallel-plate sensor model fabricated for experimentation is shown in Figure 7. Figure 8 shows the same model with the bellows sun cover removed. Figures 9 and 10 are additional views of the model. The model was designed, fabricated, and assembled on a very limited budget; consequently, many of the desired component configurations included in the schematic shown in Figures 3 and 4 (including the bellows environmental compensator) were omitted.

It was originally believed that the small temperature difference between the bellows and vapor inside would not significantly affect the system's operation. The vapor-to-bellows wall heat transfer process is convective, and the temperature difference was assumed to be negative with the vapor having a higher temperature than the bellows wall. Tests later proved this was not the case.

During tests in the morning sun, the sensor would follow the sun for approximately 30 minutes and then accelerate until the maximum rotational displacement was reached in about 45 additional minutes. The sensor's solar input area was then partially covered for the next day to reduce the heat input. The only difference observed on the following day, however, was that, after preliminary heating with the sensor at the proper tracking position, more time was required to rotate the sensor completely. In fact, with the sensor totally covered, the system would completely rotate the sensor through its 100-degree tracking angle displacement by noon, solar time.

The environmental air temperature change was believed to be the primary driver of the system and not the sensor. Insulation added to the bellows surface did slow down the angular movement speed. The sensor, when exposed with no cover, always started the angular displacement; but, once motion was started, the heat from the environment would push the sensor the rest of the way, ahead of the sun. It was concluded that the sensor was simply too small for the large bellows, especially with no bellows environmental compensator.

To determine the sensor's solar-heat input, the sensor bulb was filled with water and its temperature rise monitored for a fixed angular position. The position was 50 degrees from vertical in the eastward direction. Figure 11 shows the sensor bulb's temperature rise as a function of time. It is important to note that the unpainted metal plates permitted considerable reflective solar-heat input to the bulb.

As a result, the bulb temperature started to rise with an angle error of more than 3 degrees (4 minutes per degree) rather than one-half of 1 degree as expected. It is recommended, therefore, that the parallel plates be coated with anti-reflective ridges, as shown in Figure 4. The weights of the sensor tube and water were measured and these quantities multiplied by their respective specific heats and temperature change. Thus, the Q input was determined to be a maximum of 0.048 Btu/min (50.7 joules/min). To raise the 5.5 pound (2.5 kg) brass bellows just 1°F (0.56°C) requires more than 0.49 Btu (517 joules). Although the real purpose of the model was to demonstrate the sensor's high sensitivity, it was fully expected that the system would accurately track the sun. However, in the first attempt the system simply did not work as planned. Again, it was concluded that the sensor was simply too small for the large bellows of the model fabricated.

Economic Analysis

For the Navy to compare quantitatively all the energy research and development projects and to determine economically the funding priorities, CEL believes a uniform life cycle cost approach is essential for all the proposed projects. The ingredients for life cycle cost analysis are the capital investment for the installation, annual operating and maintenance (O&M) costs, and the economic life of a product. The capital and operating costs are estimated in as much detail as necessary to develop concepts and designs to minimize product cost requirements as well as to meet operational needs. Because the Navy currently has no need to develop a more economical device for tracking the sun, a comparison of the proposed tracker with a currently available tracker is not appropriate. Generation of steam via a solar-powered boiler, if found more economical than a coal-fired boiler currently used by the Navy, would justify development of the proposed solar tracker.

To conform to the Navy philosophy given in Reference 2, present value life cycle cost is used. For the case where the energy output of the proposed unit is constant, such as with a solar energy boiler, the following equation applies.

$$C_{PL} = \sum \frac{I}{\sum_{n=1}^{N} PV_n E_{on}} + C_{FA} + \sum C_{O\&Mn} \tag{4}$$

where C_{PL} = total present worth based on annual life cycle cost, \$/mBtu

I = capital investment for major facility components, \$

E_{on} = annual energy output of the device, mBtu

PV_n = present worth factor for nth year (Table B of Appendix D in Reference 2)

C_{FA} = levelized fuel cost to operate the product proposed (zero for the solar tracking system)

$C_{O\&Mn}$ = annual O&M cost of major facility components

It is important to note that Equation 4 is normalized per unit energy output of the device because the cumulative-energy/present-worth method will yield cost figures comparable to those from the utility and manufacturing industries (Ref 3).

The following capital cost contribution is determined for a single two-axis reflector having a reflective surface area of 10 sq ft (0.93 sq m) (see Figure 12 for illustration). For this analysis, the solar boiler and its steam distribution system costs are assumed to be the same as those for the currently available coal-fired systems. The sum total cost for energy output for a coal-fired system (coal handling, ash disposal, particulate control, and sulfur control equipment, plus their construction and setup cost) is compared to the cost per unit energy output* of a solar reflector system. In other words, the costs for the boiler system as well as the ultimate use – steam heating or electricity – are assumed to be the same for either system.

The annual usable energy output (i.e., available at the boiler for generation of steam) is estimated as follows:

$$E_{on} = \eta E_s T a$$

where η = 56% (10% loss to clouds, 30% reflection loss and 10% absorption loss at the boiler)

E_s = 2.25×10^{-4} mBtu/hr-ft^2, solar energy available at the earth's surface (2.56 mj/hr sq m)

T = 2,190 hr/yr (6 hr/day at 365 day/yr)

a = 10 sq ft, reflector surface area (0.93 sq m)

I = \$1,255 (see Table 1)

The annual capital cost contribution would then be

$$\sum \frac{I}{\sum_{n=1}^{N} PV_n E_{on}} = \$1{,}255 \left[(7.98)(0.56)\left(2.25\times10^{-4}\,\frac{\text{mBtu}}{\text{hr ft}^2}\right) \cdot \left(\frac{2190\ \text{hr}}{\text{year}}\right)(10\ \text{ft}^2)\right]$$

$$= \$57/\text{mBtu}\ (\$0.054/\text{mj})$$

where 7.98 is the present worth factor at 10% discount for a 15-year period (the expected life of the solar reflector and tracker unit).

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*This is based on the Btu's available to the boiler.

The O&M costs are assumed to be \$1.50 for labor and \$0.10 for solution to clean the reflector each year. Required spare parts and needed maintenance labor costs are assumed to total \$10/reflector/year. The resulting total annual life cycle cost for just the reflector system would be

$$C_{PL} = \frac{\$57}{mBtu} + \frac{\$11.6}{mBtu} = \frac{\$68.6}{mBtu} \quad (\$0.065/mj)$$

The annual life cycle cost of an equivalent central coal-fired steam plant including all the related cost such as fuel handling, pollution equipment, and a 5% differential coal escalation rate, is \$4.67/mBtu (\$0.0044/mj) (Ref 4). This cost also includes the boiler and its steam distribution system, which were not included in the solar system. Obviously, it would appear that construction of a solar steam generator plant for immediate Navy use would not be a profitable venture at the present time. This is not to say that solar steam generation should not be undergoing research at the present time, however. Supply and demand will push the cost of coal continually upward, and development of new, reliable hardware is a time-consuming process.

CONCLUSIONS

1. Although no working model was produced to verify the concept of a workable, accurate, solar tracker, the analysis presented is believed to be adequate proof that the concept is a viable system for accurately repositioning a solar concentrator.

2. Similarly, it is believed that once the concept is proved workable and accurate, the device should also prove highly reliable because of its simplicity.

3. The economic analysis indicated that currently a solar steam boiler would not be an economical system; however, because present energy-converting equipment use limited resources that add costly pollutants to the environment, it is very unlikely a solar boiler for a solar tracking system will remain uneconomical for long.

RECOMMENDATIONS

It is recommended that

1. More detailed analytical analysis of the two new concepts be completed.

2. One model of each concept be constructed, instrumented and tested to verify the concept and analysis.

3. The combined results be published and made available for commercial development.

REFERENCES

1. E. A. Farber, C. A. Morrison, and H. A. Ingley. "A self-contained solar powered tracking device," paper presented at American Society of Mechanical Engineers Winter Annual Meeting, New York, N.Y., 2 Dec 1976. (ASME Paper 76-WA/HT-76)

2. Naval Facilities Engineering Command. NAVFAC P-442: Economic analysis handbook. Alexandria, Va., Jun 1975.

3. Civil Engineering Laboratory. Economic analysis and priority rating formulation for Navy shore facilities energy R&D products, by J. M. Slaminski. Port Hueneme, Calif., Nov 1977.

4. ___________. Naval shore establishment energy research and development program, First FY-78 program review. Port Hueneme, Calif., Apr 1978, pp 13-14.

Table 1. Capital Cost for a Two-Axis Solar Reflector With 100-Square-Foot Surface Area

Item	Cost ($)
Research and Development Design	50
Setup	100
Reflector Frame	400
Two-Axis Trackers	600
Foundation	50
Mylar Reflector ($0.15/sq ft)	15
Land Procurement	40*
TOTAL	1,255

*250 reflectors/acre at $10,000/acre.

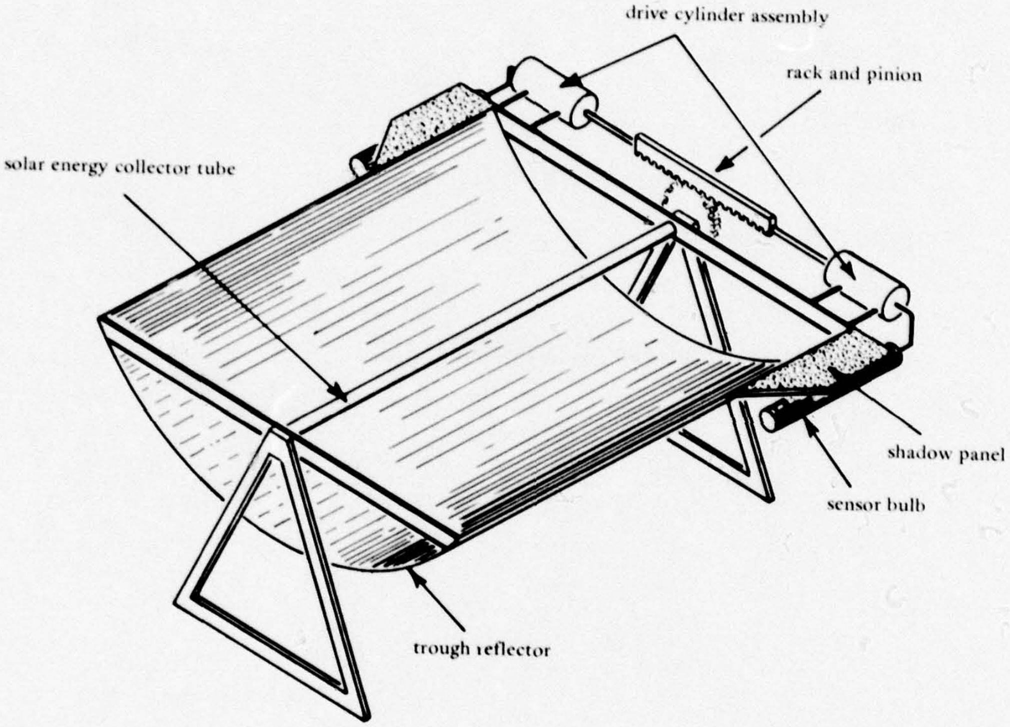
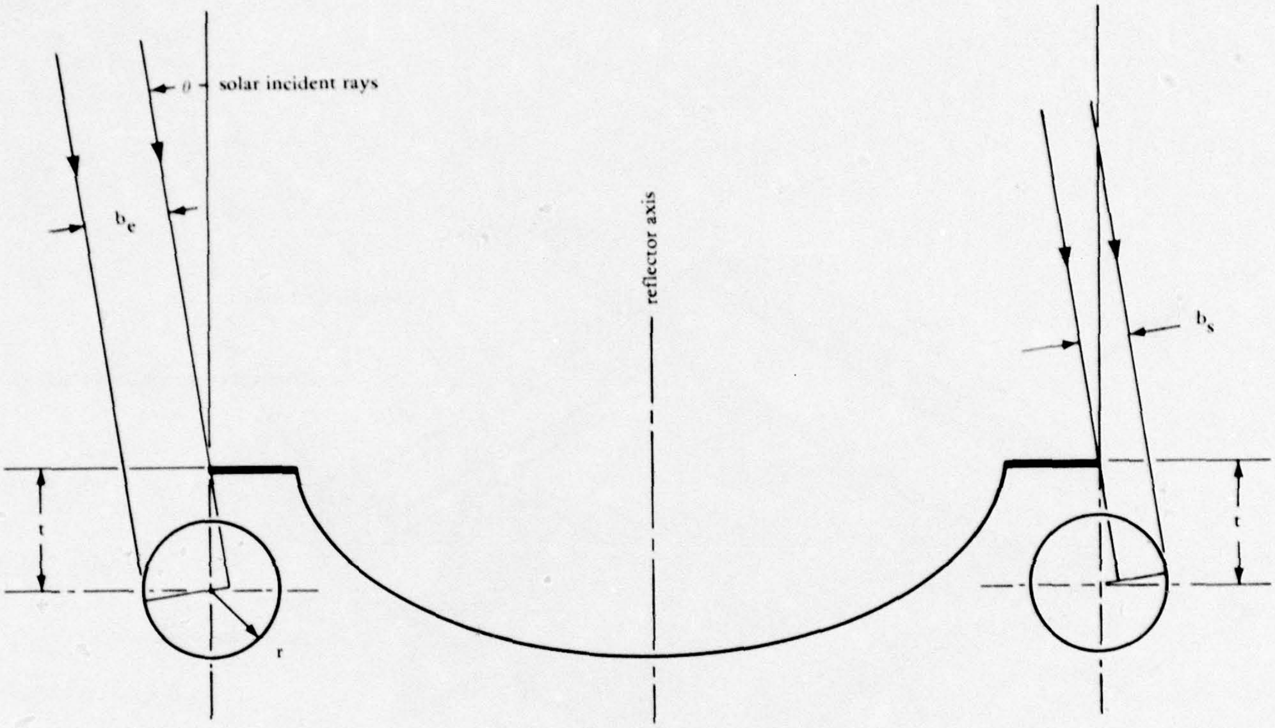


Figure 1. Farber, Morrison, and Ingley solar-powered tracker.



$$b_e = r + t \sin \theta$$

$$b_s = r - t \sin \theta$$

$$Q \cong \epsilon \sigma F L (b_e - b_s)(T_s{}^4 - T_b{}^4)$$

$$Q \cong 2 \epsilon \sigma F L t \sin \theta \, (T_s{}^4 - T_b{}^4) \text{ for } \sin^{-1}\left(\frac{r}{t}\right) \geq \theta \geq -\sin^{-1}\left(\frac{r}{t}\right)$$

$$Q \cong 2 \epsilon \sigma F L r \, (T_s{}^4 - T_b{}^4) \text{ for } -\sin^{-1}\left(\frac{r}{t}\right) > \theta > \sin^{-1}\left(\frac{r}{t}\right)$$

Figure 2. End view of the Farber sensor bulb, showing unequal shading system.

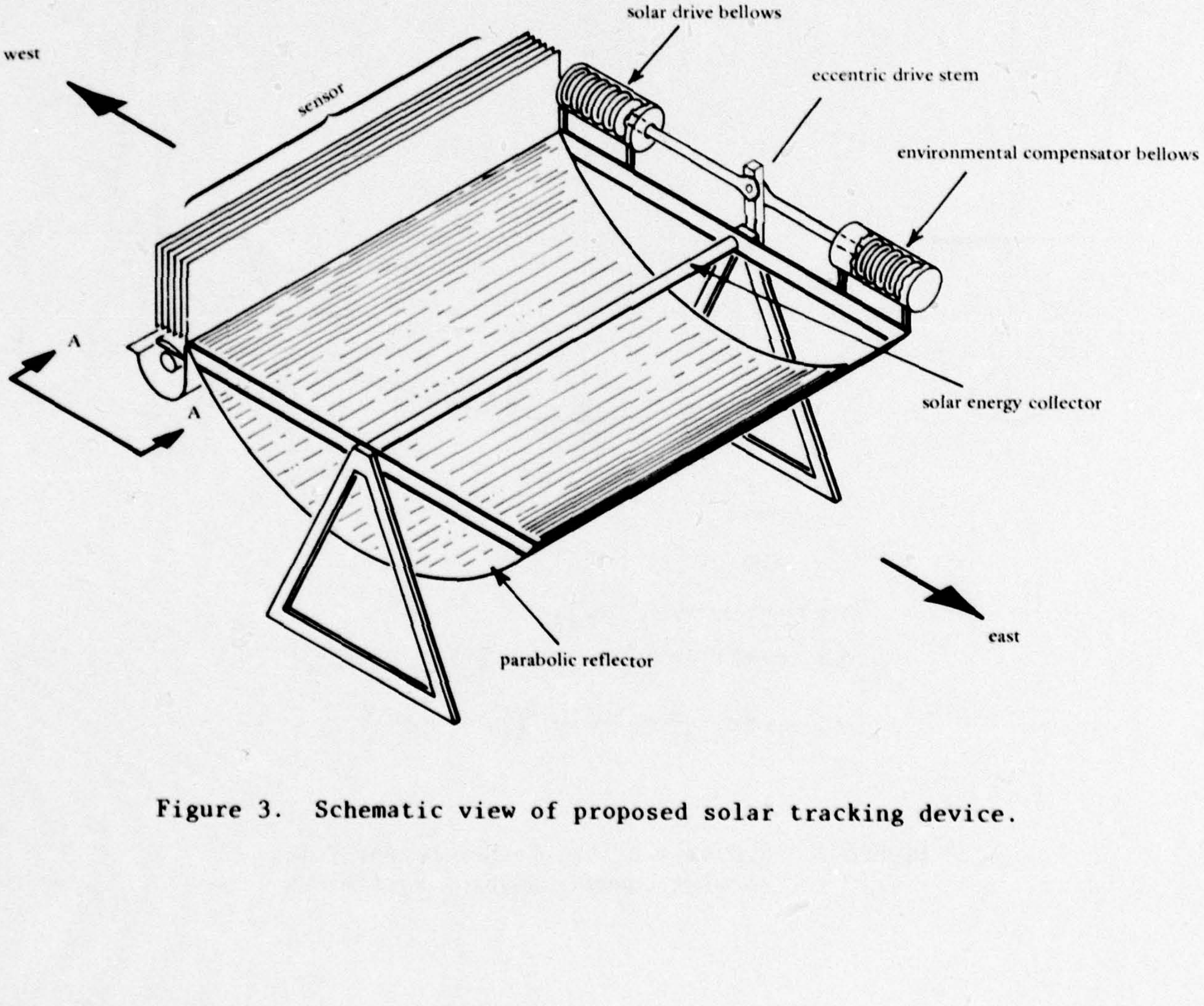


Figure 3. Schematic view of proposed solar tracking device.

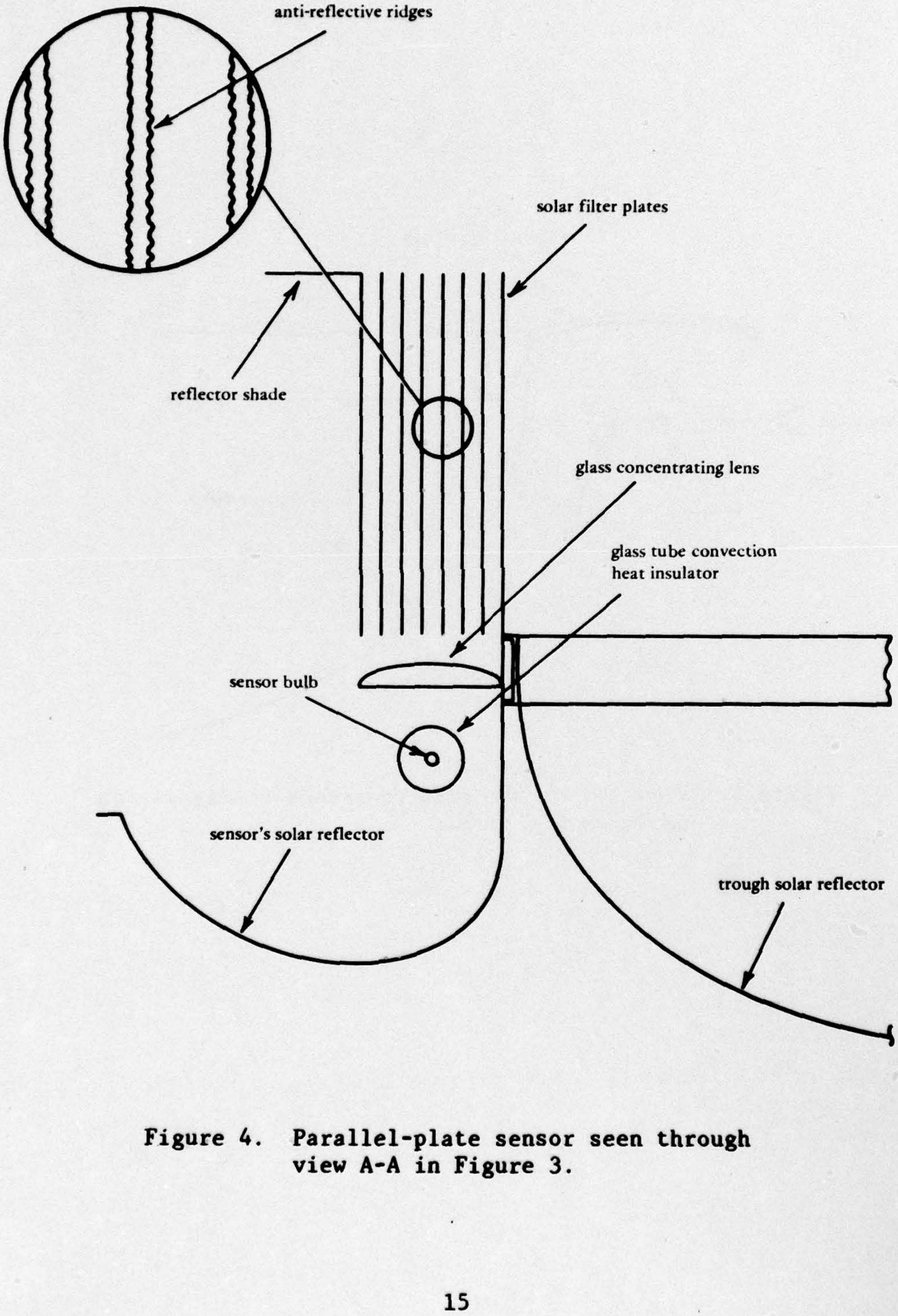


Figure 4. Parallel-plate sensor seen through view A-A in Figure 3.

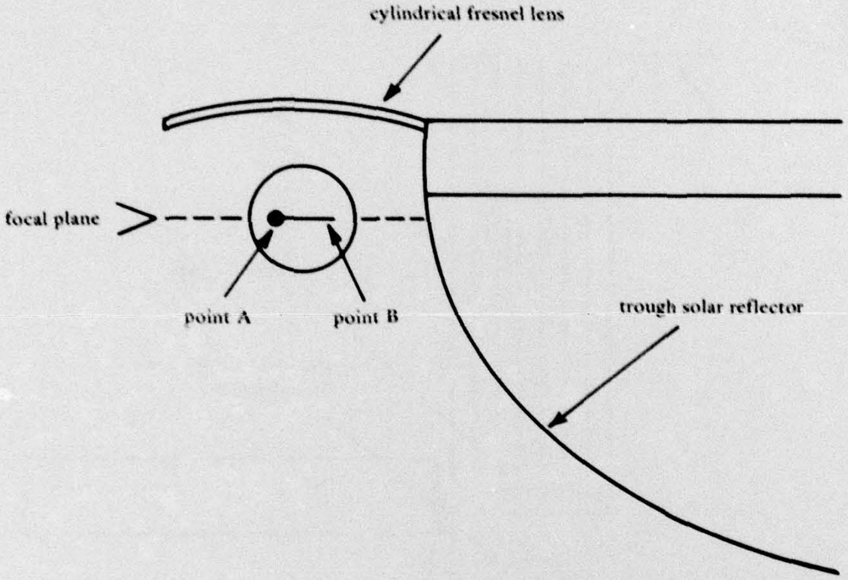


Figure 5. View A-A of alternative sensor configuration shown in Figure 3.

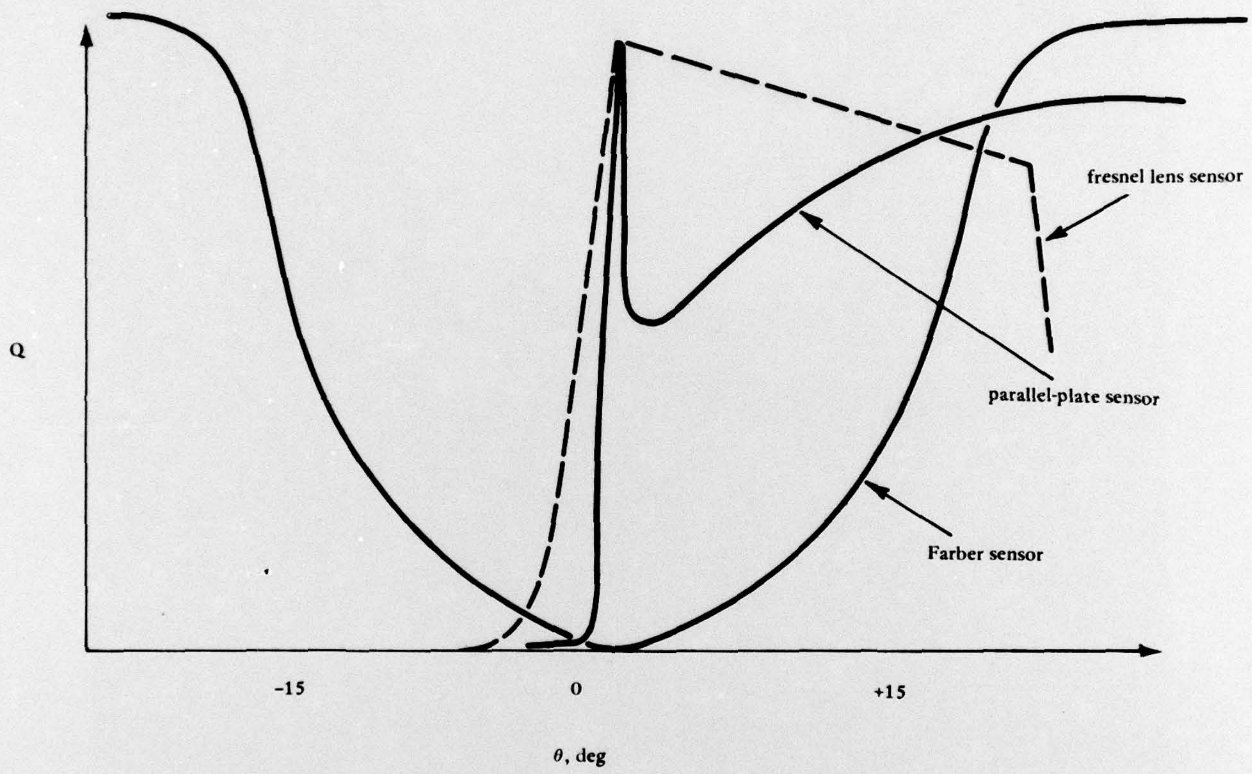


Figure 6. Differential solar energy input for the error angle between the solar incident rays and the trough reflector axis.

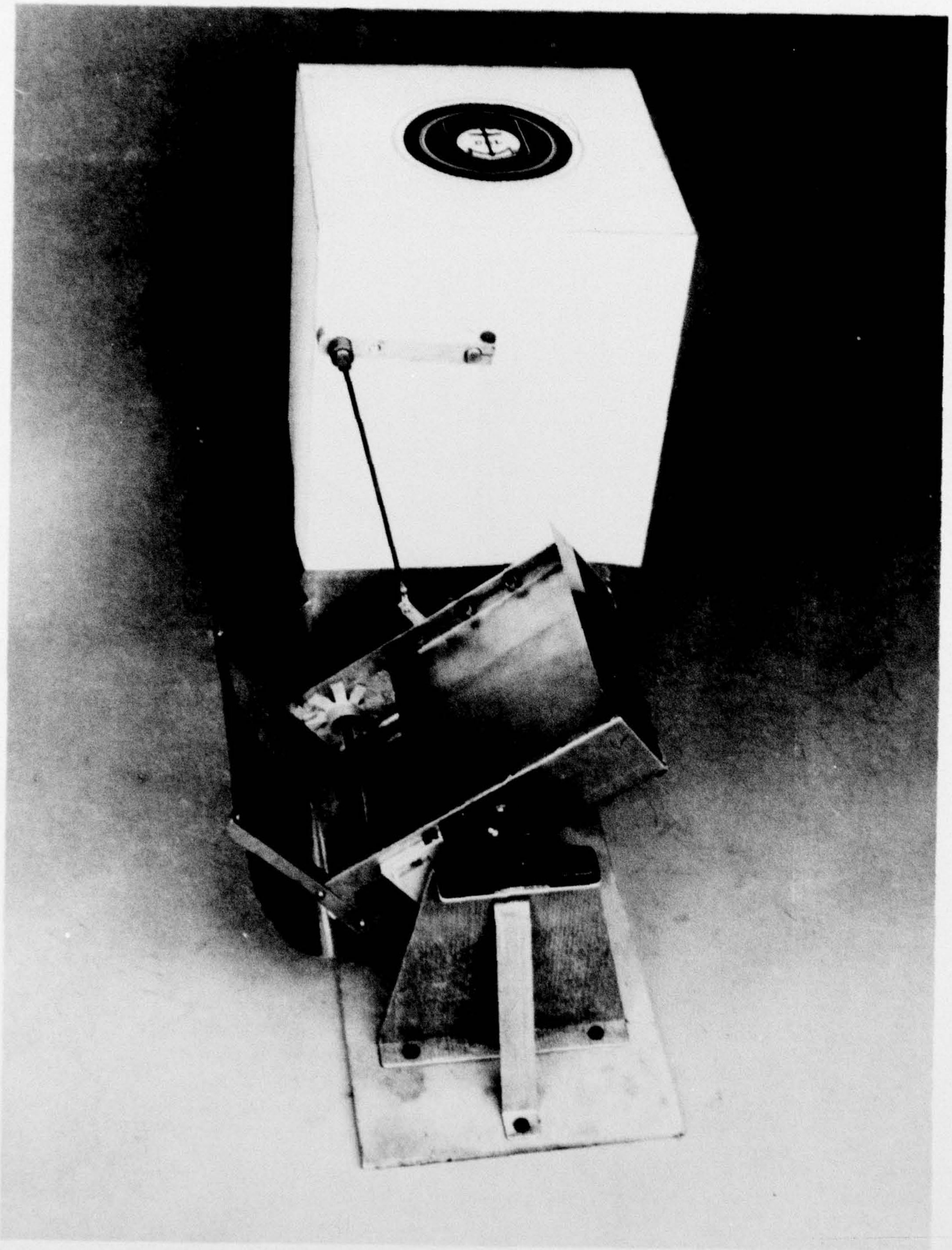


Figure 7. Experimental model of parallel-plate sensor.

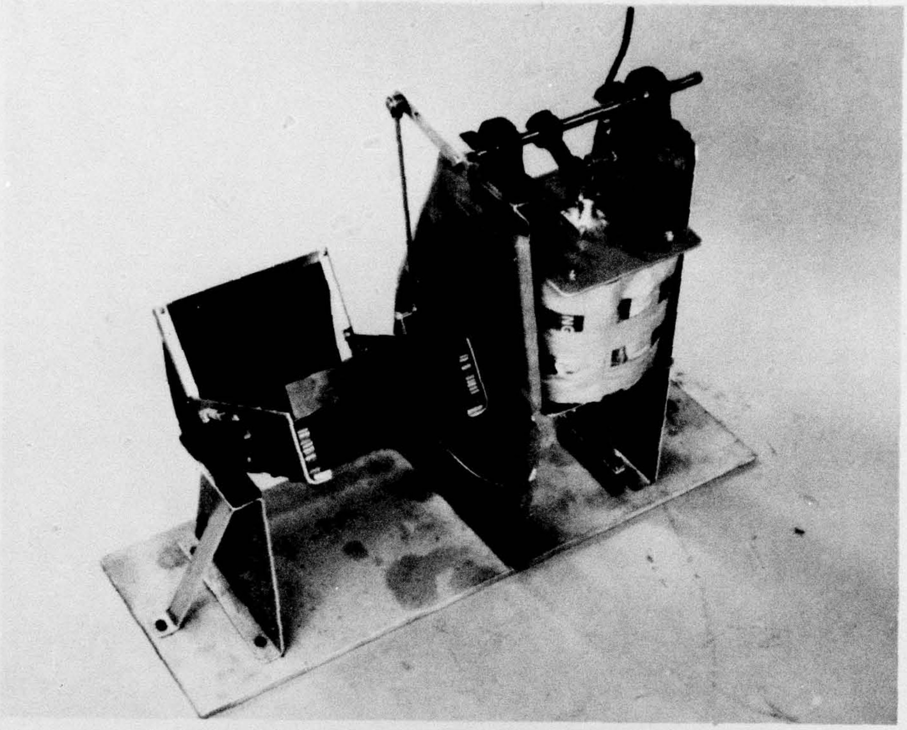


Figure 8. Experimental model with the bellows sun cover removed.

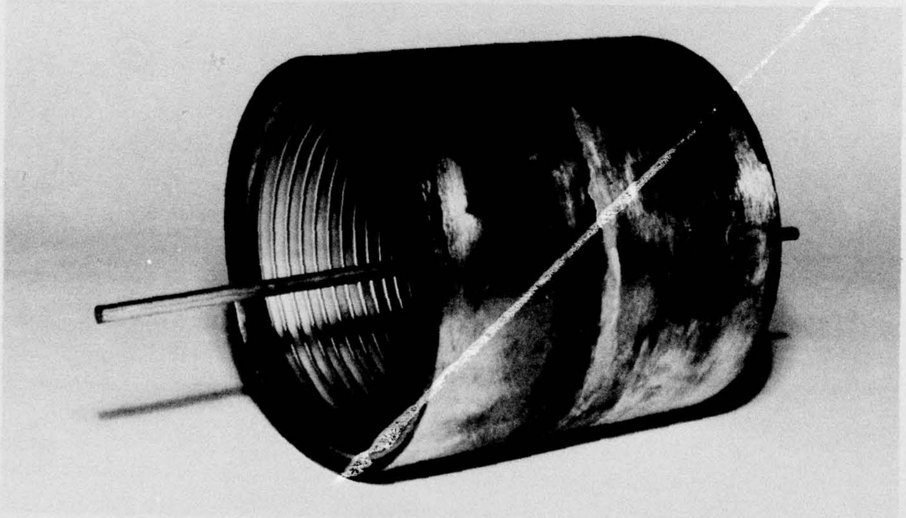


Figure 9. Close-up view of the bellows used for the experimental model of the parallel-plate sensor.

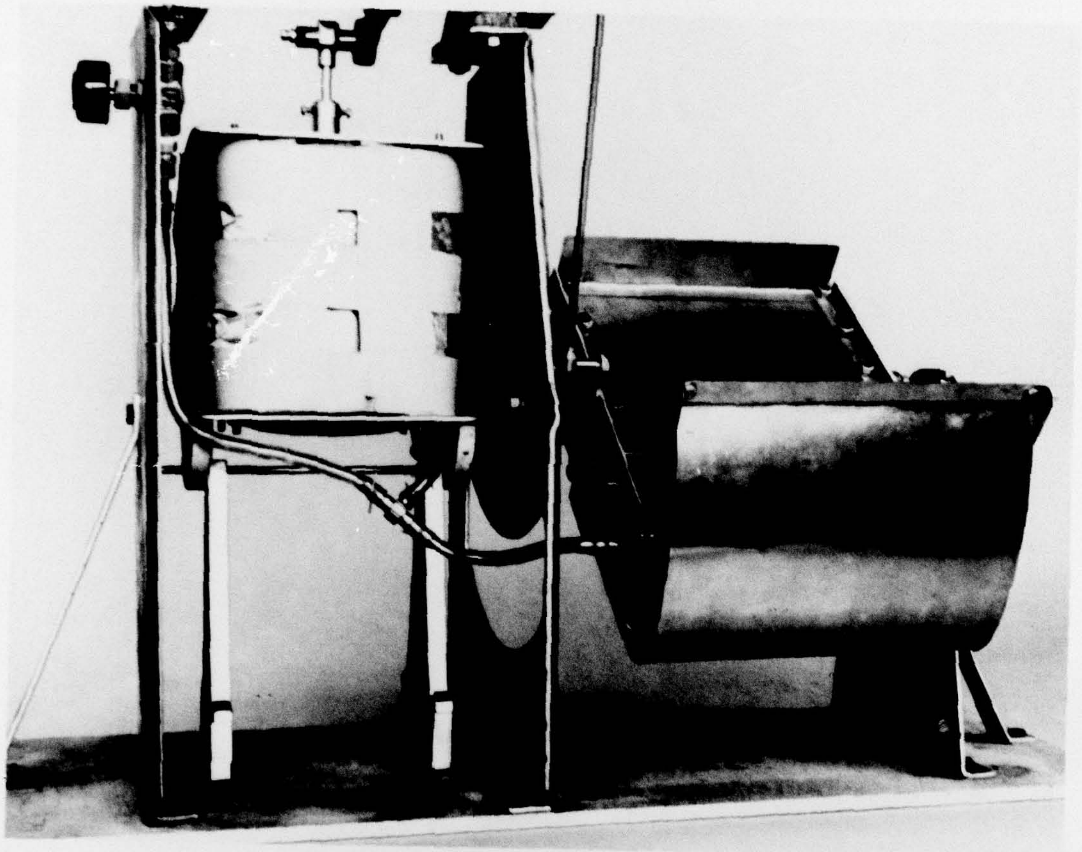


Figure 10. Close-up view of the flexible tube used to transport the working fluid vapor from the solar sensor to the bellows.

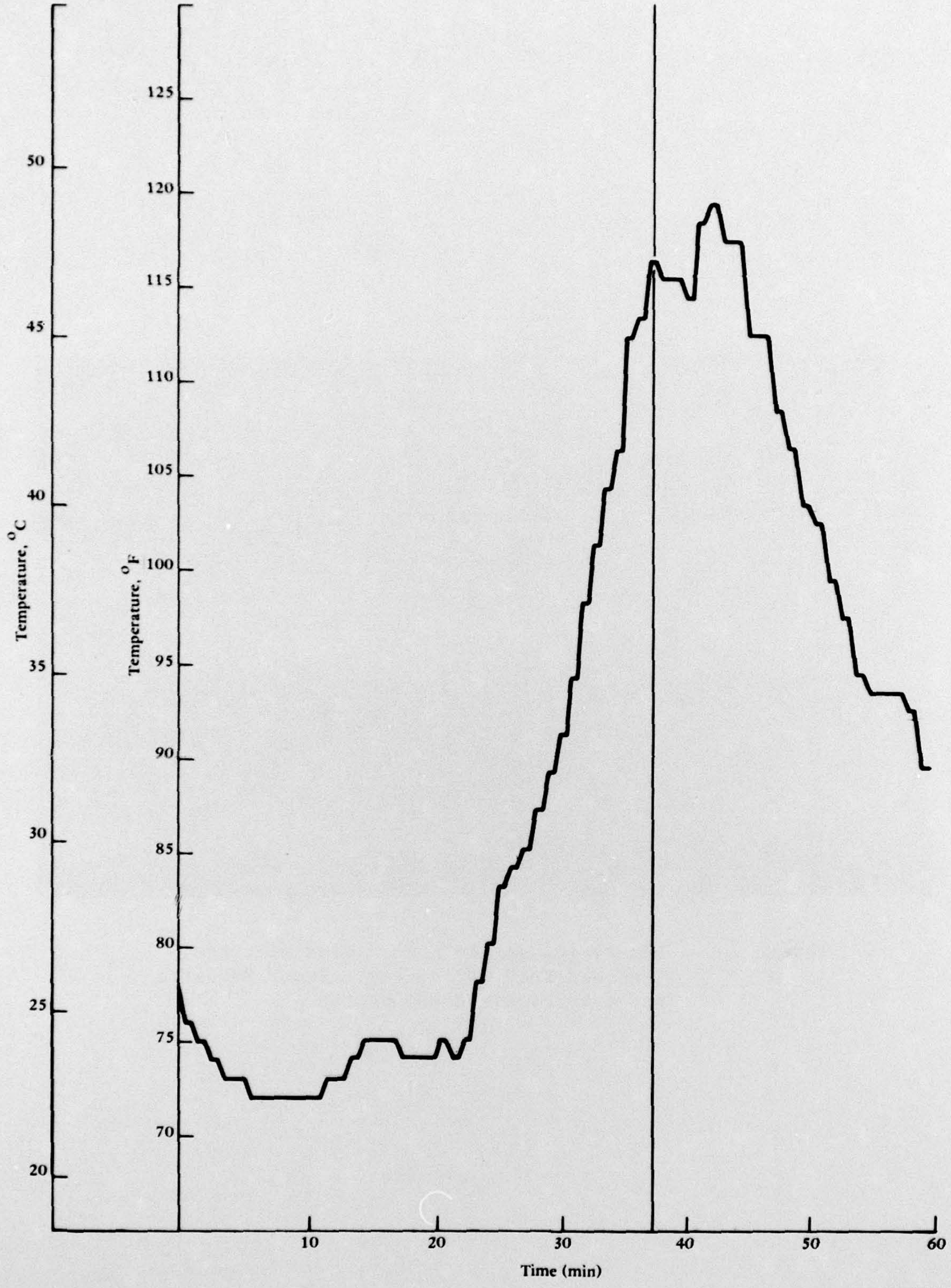


Figure 11. Temperature versus time with the parallel-plate solar sensor model positioned 50-degrees from vertical, facing due east.

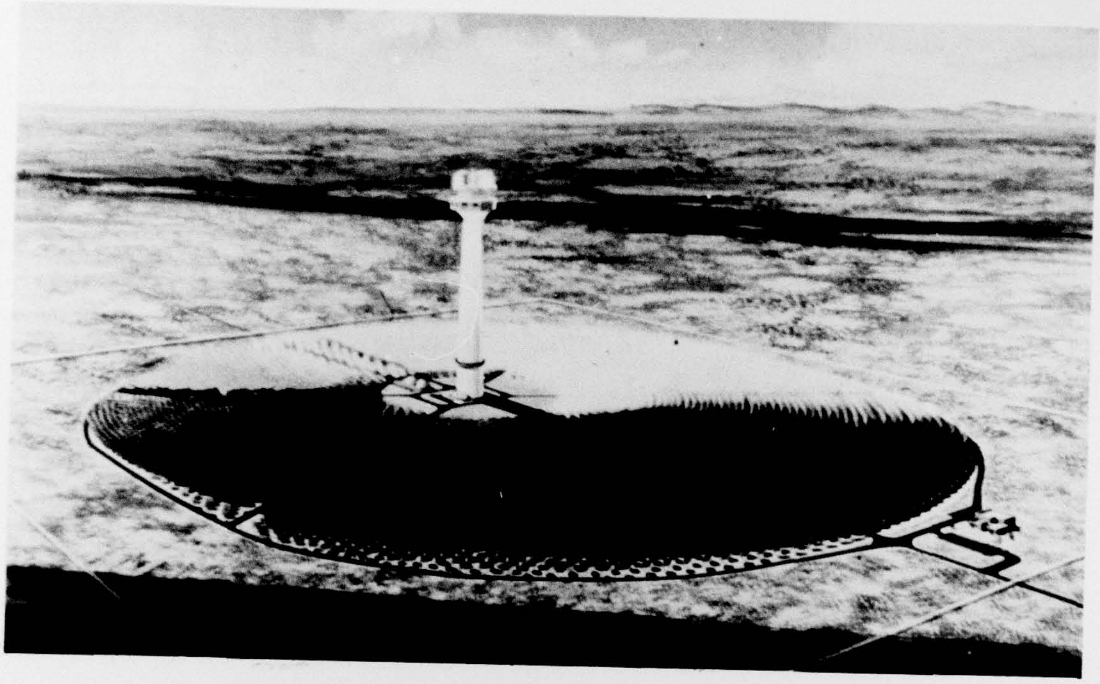


Figure 12. Open-cycle, gas turbine, solar electric plant designed for Electric Power Research Institute by Black and Veatch.

LIST OF SYMBOLS

A	System's equivalent exposure area to heat loss, sq ft (sq m)
a	Reflector surface area, sq ft (sq m)
b_e	Larger solar exposed width of collector tube, ft (m)
b_s	Smaller solar exposed width of collector tube, ft (m)
C_{FA}	Levelized fuel cost to operate the product proposed, $
$C_{O\&Mn}$	Annual O&M cost of major facility components, $
$C_p W \Delta T$	Equivalent heat absorbed into the system, Btu (joule)
C_{p_b}	Specific heat of sensor tube material, Btu/lb-°F (joule/kg °K)
C_{p_c}	Specific heat of the cylinders and piston material, Btu/lb-°F (joule/kg °C)
C_{PL}	Total present worth based on annual life cycle cost, $/mBtu ($/joule)
E_{on}	Annual energy output of the device, mBtu (joule)
E_s	Solar energy available at the earth's surface, Btu/sq ft hr (joule/sq m hr)
F	View factor
f	Focal length of the trough's reflector, ft (m)
h_c	System's average heat-loss convection coefficient, Btu/hr-sq ft-°F (watts/sq m °K)
h_f	Working liquid fluid enthalpy, Btu/lb (joule/kg)
h_{fg}	Heat of vaporization of the working fluid, Btu/lb (joule/kg)
h_g	Working gas fluid enthalpy, Btu/lb (joule/kg)
I	Capital investment for major facility components, $
J	Mechanical equivalent of heat, 778 ft-lb/Btu (1 Nm/joule)
L	Collector tube length, ft (m)
N	Economic life, yr
PV_n	Present worth factor for nth year
Q	Differential solar energy input to the sensor tubes, Btu (joule)
Q_{loss}	Energy lost through convection, Btu (joule)
r	Collector tube radius, ft (m)

T	Solar tracker operating time per year, hr/yr
T_b	Collector tube surface temperature, °R (°K)
T_s	Equivalent temperature of the solar radiation, °R (°K)
T_μ	Resisting frictional torque of the trough, ft-lb (Nm)
t	Distance from sun shade to center of collector tube, ft (m)
W	Work available to rotate device, ft-lb (Nm)
W_b	Weight of sensor tubes, lb (kg)
W_c	Weight of the cylinders and pistons in contact with the working fluid, lb (kg)
W_f	Weight of working fluid, lb (kg)
W_{fg}	Weight of working fluid evaporated, lb (kg)
W_g	Weight of working fluid in gas phase, lb (kg)
β	Required angle the trough must rotate in the Δt time period to track the sun's movement
Δh_f	Change in enthalpy of working fluid, Btu/lb (joule/kg)
Δh_g	Change in enthalpy of working fluid in gas phase, Btu/lb (joule/kg)
ΔT	Average change of temperature of the complete system including sensor tube, cylinders, pistons, and working fluid, °F (°C)
Δt	Time period of analysis, hr
ε	Emissivity of collector tube
η	Energy conversion efficiency, %
θ	Angle of solar tracker from vertical
σ	Stefan-Boltzmann universal constant for black-body radiation, Btu/sq ft hr $°R^4$ (joule/sq m hr $°K^4$)

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