N78

19041

UNCLAS

A LOW COST HIGH TEMPERATURE SUN TRACKING SOLAR ENERGY COLLECTOR

By Gerald S. Perkins

Jet Propulsion Laboratory
Pasadena, California

ABSTRACT

This paper will describe the design and economic evaluation of a low-cost high-temperature two-axis sun tracking solar energy collector. The collector design is specifically intended for solar energy use with the freedom of motion about its two control axes being limited only to the amplitude required to track the sun. An examination of the performance criteria required in order to track the sun and perform the desired solar energy conversion is used as the starting point and guide to the design. This factor, along with its general configuration and structural aspect ratios, is the significant contributor to achieving low cost. The unique mechanical design allows the control system to counter wide tolerances that will be specified for the fabrication of the azimuth frame and perform within a small tracking error.

INTRODUCTION

In answer to the question "Why is the solar concentrating two-axis tracker preferred?", two of the key factors in evaluating the relative performance of various collection systems are:

(a) How much of the available solar energy is "harvested" each year?
(b) What is the net overall plant conversion efficiency?

A comparison of solar energy collected by typical non-tracking, single-axis and two-axis tracking collector designs for a fall day at Albuquerque, N.M., is shown in Fig. 1. The approximate seasonal variation for the same three designs at the same locations is shown in Fig. 2.

The ability of the two-axis system to harvest 78-80% of the available direct normal insolation, whereas the single-axis collects 30-35% and the non-tracking 17-20%, holds for most locales of interest to potential users.

It should also be noted that the temperature of collection is usually limited to 300-400°F for the non-trackers and 500-600°F for single-axis tracking;

This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract NAS7-100, sponsored by the National Aeronautics and Space Administration.

but temperatures in the 1000-2000°F range may easily be attained by two-axis tracking. Thus, for both questions (a) and (b) above, the two-axis system is clearly superior. The bottom line, of course, is not determined solely by (a) and (b), but must also consider such items as initial cost, operating costs, etc. The key to taking advantage of the much higher potential performance of the two-axis system is to achieve initial cost and operating expense levels which will be less in proportion than the factor of 3-10 advantage in relative performance. Figure 3 shows a comparison of the costs per kWe for the three collector designs studied previously, when realistic cost figures were added to the performance calculations. As may be seen, the two-axis performance was better by a factor of two, even though a collection temperature of only 1000°F was assumed.

The major conclusion here is that two-axis tracking is clearly superior in potential thermal performance; so, if initial cost and operating expenses can be held to a level, which will not offset this advantage, two-axis tracking is the appropriate choice. The key will be to achieve low cost ($16/ft^2$). The $16/ft^2$ cost figure is for a complete solar conversion system with electrical output from solar energy input.

DESIGN DESCRIPTION

The control axes, azimuth, and elevation are arranged to intersect at the focal point of the parabola. Figure 4 illustrates the design configuration of the sun tracking solar energy collector. The structure which will support the reflecting surface rides on wheels captured in curved channel rails on top of the azimuth structure. The azimuth structure is supported and restrained at the center by a pivot anchored in concrete and by two wheels on a peripheral circular track near its outer end. The parabola structure is counterbalanced about its elevation axis by a pendulum cable system.

Figures 5, 6, and 7 also illustrate the design configuration of the 50 ft solar tracking collector. The parabolic reflector has a focal length to diameter ratio of 0.5. The structure that will support the reflecting surface rides on wheels captured by curved rails on top of the azimuth frame. This provides the elevation axis motion. The structural relationship between the reflector support structure and the azimuth frame is a triangular (3 point) load transfer configuration. This kinematic relationship will prevent a deflection of either structure from imposing a strain on the other. This kinematic feature will also allow large tolerances on the order of ± one inch radial deviation to be used in the fabrication of the azimuth frame curved rails. The elevation drive is provided by a tensioned chain looped around the drive sprocket of the elevation actuator.

The azimuth frame is supported and restrained at the center by a pivot anchored in concrete and by a system of wheels on a peripheral track near its outer end. This allows the azimuth motion. One of the wheels is driven by the azimuth actuator in order to provide the azimuth drive motion. Both the elevation and azimuth actuators are coupled to their respective drive systems with effectively antibacklash linkages. This will allow the use of standard commercial gearboxes for the makeup of the drive actuators since they will be placed ahead of the output coupling of ratio [illegible]. The output drive ratio [illegible] is friction coupled in the azimuth drive and torque biased in the elevation drive. This condition will eliminate output ratio backlash from either axis. The output drives can be described as antibacklash drives. The backlash from the gearboxes will now be reduced by $1/\eta$.

The expected resultant backlash as seen by the control system is now in the higher speed regimes of the actuator mechanisms and is shown to be reduced by the following relationship:

$$\text{output backlash} = \frac{\text{gear train backlash}}{\text{output ratio}}$$

$$\text{output ratio } A_z = \frac{\text{support track dia}}{\text{drive wheel dia}} > 30$$

$$\text{output ratio El} = \frac{\text{drive chain trough radius}}{\text{elevation actuator drive sprocket radius}} > 50$$

$$\text{output backlash} \leq 0.05°$$

The fixed focal point concept provided by the intersection of the elevation and azimuth axes at the focal point of the parabolic reflector will allow the heat engine or receiver to be mounted independently of the parabolic reflector and its structure. The heat engine or solar flux receiver is mounted separately on a small tower. It may be mounted in a gimbal and tethered to the parabola structure by a system of cables. This will keep the receiver pointed along the axis of the parabola. The cables will be equipped with spring damping systems in order to minimize dynamic interaction between the separate structures that might be caused by wind induced vibration.

The mirror surface is made by mounting second surface glass mirror segments to a series of monocoque panels that will cover the parabolic structure. The glass will be attached to the panels by discrete fasteners in order to be free of strain that is caused by thermal expansion.

A scale model of the low cost solar tracker is shown by Figs. 5, 6, and 7. The features that make this device a low cost system are discussed and listed as follows.

1. The sun will be tracked only for the purpose of energy collection, not navigation. This will allow a larger tracking error (0.1°) than is conventionally used for space navigation with resultant economies throughout the design of the mechanism and control system. A 0.1° tracking error is acceptable; this is several orders of magnitude greater than allowed for space navigation tracking. The prior technology for two-axis parabolic tracking systems is in space navigation and communication systems. This is the primary point of reference for the cost reduction.

2. The unique design configuration transfers the load from the azimuth frame to the parabolic support structure at or near the optimal restraint points of its radial trusses where the effects of the load distribution moments are minimized. This will reduce the steel usage in the parabolic structure with regard to its required loading.

3. The large tolerances allowed for the fabrication of the curved rails on the azimuth frame by the kinematic relationship between it and the parabolic reflector support structure will minimize the construction costs. The sun tracking deviations ±0.4° occurring at 0.03°/hr that might be caused by these tolerance-induced errors will be countered by the control systems with no increase in complexity or cost. The desired tracking accuracy of 0.1° will be achieved. The control sun tracking rate capability is 2000 times the rate occurrence of the error rate being corrected. The dynamic response demanded for this correction is negligible.

CONTROL SYSTEM

The actuators and drive motors will be sized to drive the tracker in the wind load condition and to drive the elevation axis without benefit of counterbalance aid. This can be as large as 500,000 ft lb in a 100 mph wind. The largest wind load the tracker is required to operate in (30 mph) should not cause torques greater than 80,000 ft lb for a 50 ft diameter parabola. The larger torque is about the azimuth axis. The actuators will not back drive because of the inclusion of a worm gear drive on the gearbox output stage. This feature will cause the tracker to be held in any shutdown position and will eliminate the need for a brake or latching device.

In order to reduce the wind strain while in the stow position (see Fig. 7) near the ground, a wind deflector fence will surround it. This fence will enhance the boundary layer properties and cause desirable lift and drag reducing turbulent flow over the parabola. The mechanical design of the tracker control system is such that it will never be overloaded in any condition of operation or stowage in winds up to 100 mph. The output stage of the azimuth drive is friction coupled. Slippage should occur at about 300,000 ft lb torque load. The actuator will tolerate greater than 800,000 ft lb torque in a static condition. A large safety margin is realized.

The control system functional parameters for operation are as listed.

1. The tracker will track the sun within 0.1° (tenth degree) accuracy in the presence of 30 mph wind loads and 39 mph gusts.

2. The tracking rate capability for either axis will range from 0 to 50° per hour.

3. The rapid slewing rate will be 550° per hour minimum for the "panic mode" (used to stow the tracker in a high wind) and eastward return.

The tracker control system consists of the following basic elements:

- microprocessor
- wide angle sun sensor
- motors
- gearboxes and related hardware
- chain and sprockets
- wire rope
- assorted electronics

The dynamic model of the solar energy collector is shown in Fig. 8. The basic philosophy of the control system is: a predetermined desired rate is modified or trimmed by actual position errors determined by a sun sensor. The controller residing within the microprocessor ensures that the tracking collector is pointed generally toward the sun in the morning and sends "start track" command. The controller constantly calculates the sun's rate for both azimuth and elevation during the day. The maximum rate for any time of the year is 50° per hour. The controller uses this "open loop" sun's rate and sun sensor information as inputs to generate proper motor commands to slew the collector. If the average wind exceeds 30 mph the collector is commanded by an operator or automated input from a wind sensor (not shown in Fig. 8) to a safe position, 90° elevation, azimuth stopped, see Fig. 7, using a fast slew ("panic mode") rate of 550°/hr. To restart, the operator turns on the system, the collector reacquires the sun and resumes tracking. If clouds mask the collector sun sensor the open loop rate command stored in the microprocessor will drive the system. Upon unmasking the sun sensor will trim the collector position. The control system will assume the closed loop method of control.

ECONOMIC EVALUATION AND COSTS

From the introduction it is seen that a two-axis sun tracking system is the most economic of the three types compared. The cost goal of $16/ft^2 for a two-axis system is derived from a series of studies relating to the economic use solar energy. All seem to converge on the $16/ft^2 cost figure as an upper limit.

In order to estimate the costs the assembly is broken into its component parts with each part being separately costed out. Tooling and process planning is included in the cost figures. The cost of all materials and hardware parts were discussed with sales managers of representative companies. All companies contacted have sales, price, and delivery experience relating to this type hardware. Tooling and process planning was reviewed with representative manufacturing companies. The cost estimation is made for prototype and pilot production, through limited and finally large scale production. Figure 9 is a tabulation of these cost data.

The labor/materials ratio tends to approach a lower limit of one with adequate tooling and coordinated production procedures. Figure 10 is a graphic presentation of the cost versus production quantity and shows that the low cost goal of $16 per square foot previously mentioned in the economic analysis and cost section can be achieved with modest production quantity. A comparison of collector size versus cost is displayed by Fig. 11. The indication is that a 60-foot diameter parabolic tracking collector appears to be a cost optimum.

SUMMARY

Based on the study and analysis performed for the design of two-axis solar concentrating tracker, the following observations can be made.

- The low cost goal $<\$16$ per ft^2 appears to be achievable.
- Two-axis sun tracking produces more power than any of the other systems compared for less cost.
- The tracking assembly can be constructed using standard parts and conventional materials.

ACKNOWLEDGMENT

Mr. John C. Becker of JPL provided the sun tracking system comparative data used in the introduction.

Dr. Robert O. Hughes of JPL performed the control system design.

Dr. Roy Levy and Mr. Smoot Kato, both of JPL, performed the structural design analysis that was required in order to evaluate the design.

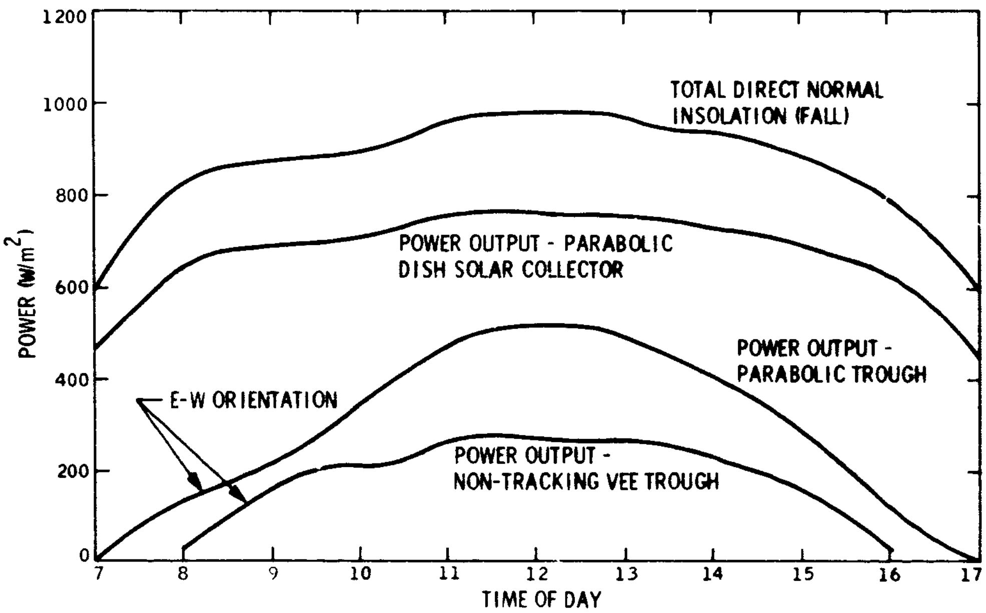

Fig. 1. Comparison of solar power collected by different collector designs (Albuquerque, N.M.)

WATT-HOURS/m^2

COLLECTOR	SPRING	SUMMER	FALL	WINTER
PARABOLIC DISH (2 AXIS TRACKING)	7408	8113	7298	6049
PARABOLIC TROUGH (E-W; 1 AXIS TRACKING)	2978	3443	3002	2945
VEE-TROUGH (NON-TRACKING)	1633	2002	1645	1876

Fig. 2. Total energy collected by three collector designs (per day - Albuquerque, N.M.)

	COST	TOTAL ENERGY COLLECTED PER DAY	AVERAGE POWER COLLECTED PER DAY	COST PER KILOWATT THERMAL	TEMPERATURE OF COLLECTION	COST PER KILOWATT ELECTRIC*
	$/ft^2	Wh/m^2	W/ft^2	$/kWt$_{avg}$	deg F	$/kWe$_{avg}$
PARABOLIC DISH (2 AXIS TRACKING)	13.49	7298 (7[illegible])	61.6	217	1000 F	505
PARABOLIC TROUGH (1 AXIS TRACKING)	[illegible].97	3002 (32[illegible])	25.[illegible]	[illegible]	600	1080
VEE TROUGH CONCENTRATOR (NO TRACKING)	4.10	1[illegible]5 (17.6[illegible])	1[illegible].9	[illegible]	450	1090

TOTAL ENERGY AVAILABLE PER DAY (FALL AVERAGE) 9350 w-hr m^{2}

THERMAL ENERGY CONVERSION TO ELECTRIC AT 70 CARNOT EFFICIENCY USING
100 F REJECTION TEMPERATURE

Fig. 3. Calculated Fall (season) performance of collector types at Albuquerque, N.M.

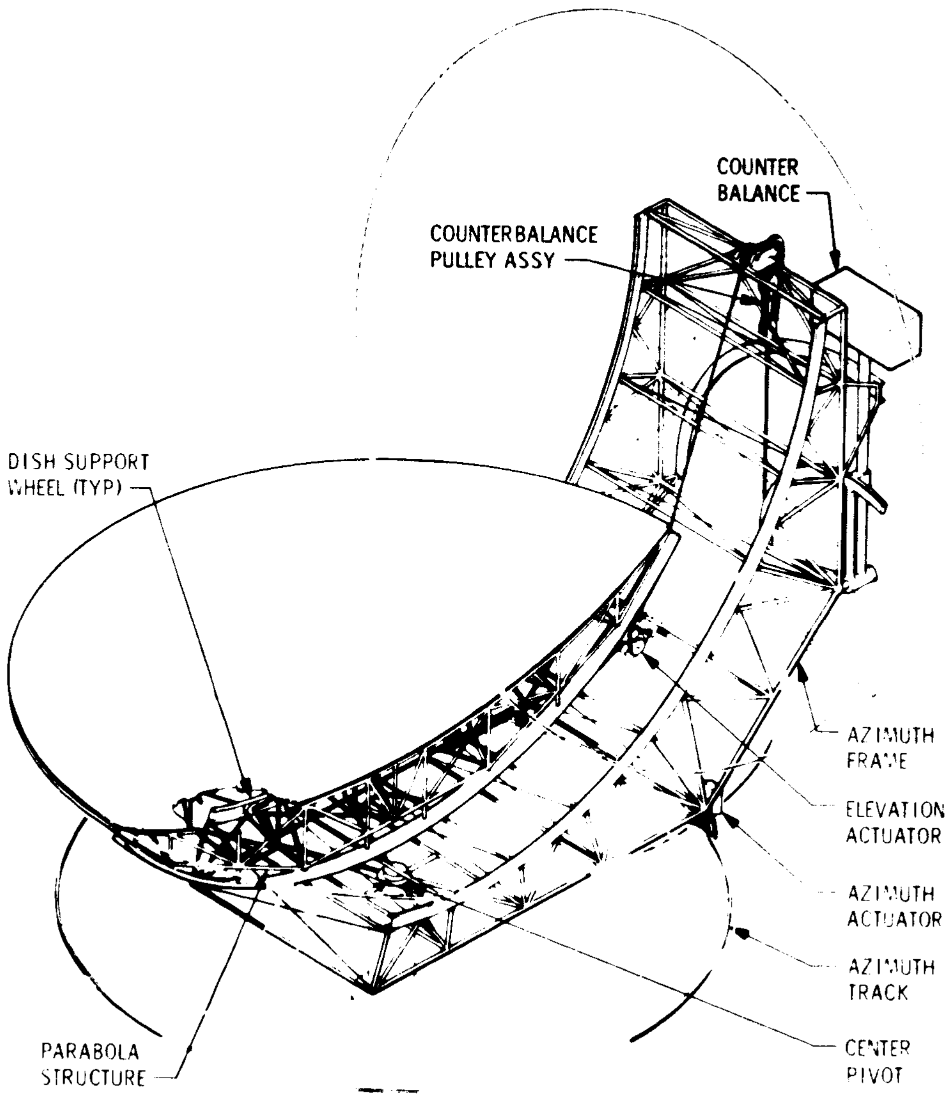

Fig. 4. Solar tracker assembly

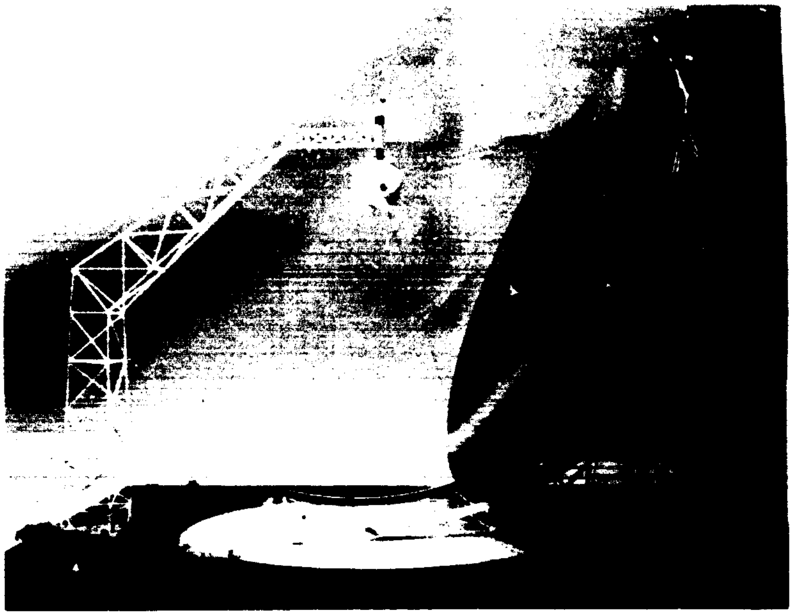

Fig. 5. Solar tracker assembly, side view

Fig. 6. Solar tracker assembly, rear view

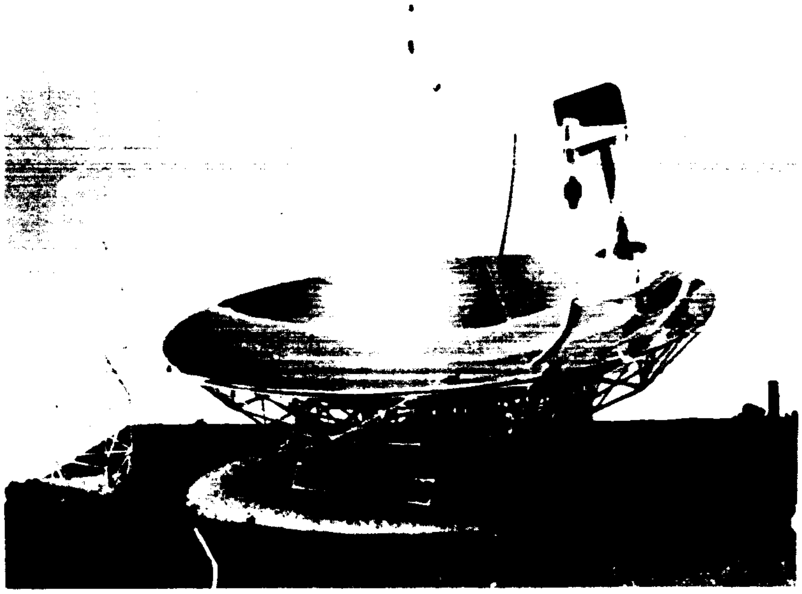

Fig. 7. Solar tracker assembly, stow position

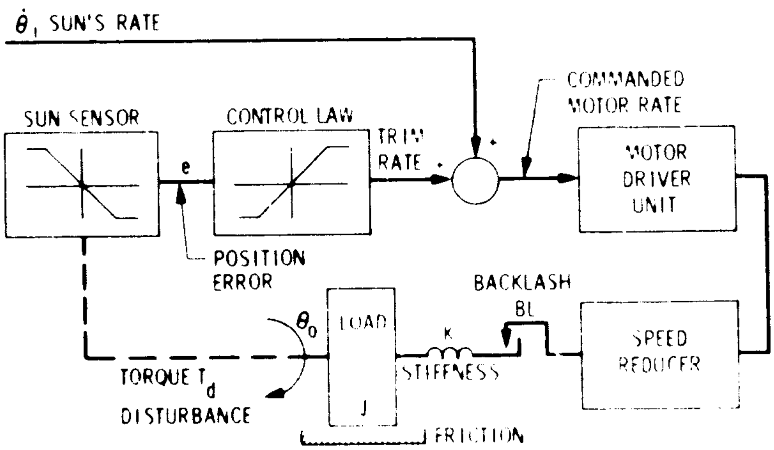

Fig. 8. Collector control system, typical for either axis

COST	PROTOTYPE	3-10 UNITS	10-100 UNITS	100-1000 UNITS	50 000 UNITS
COST PER FOOT^2	60	21.25	16.27	12.97	9.93
STEEL FABRICATION COST PER POUND	3.38	2.40	1.71	1.39	1.10
LABOR/MATERIALS RATIO	5.01	1.36	1.17	1.13	1.11

Fig. 9. Economic and cost data

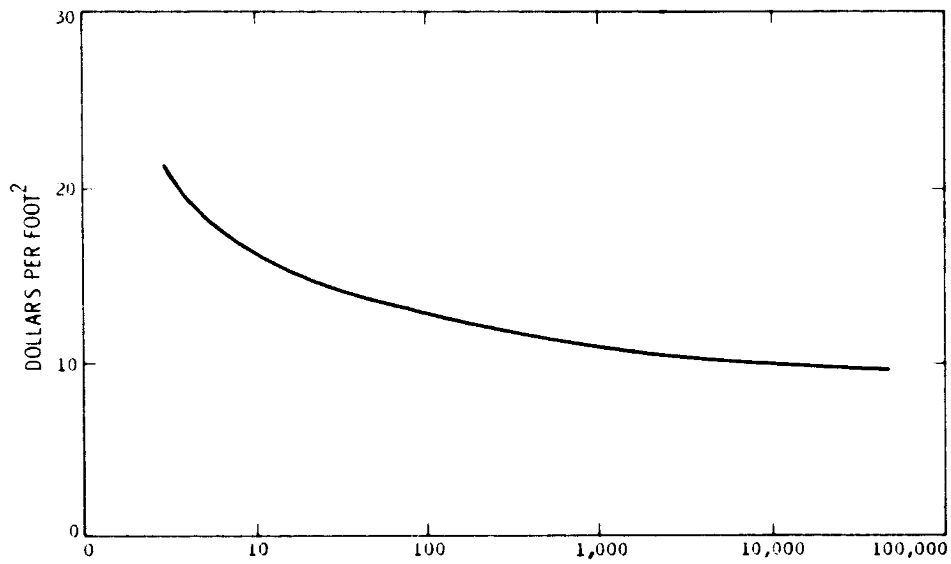

Fig. 10. Collector manufacturing lots

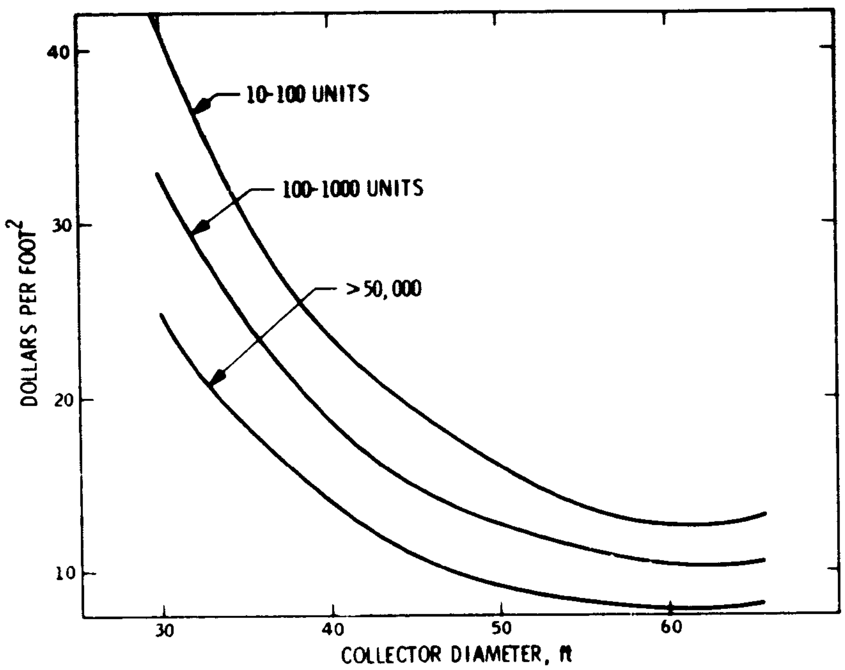

Fig. 11. Collector size cost comparison

N78

19042

UNCLAS