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The Credibility of Cost Estimates for Mass-Produced Heliostats

E. D. Eason

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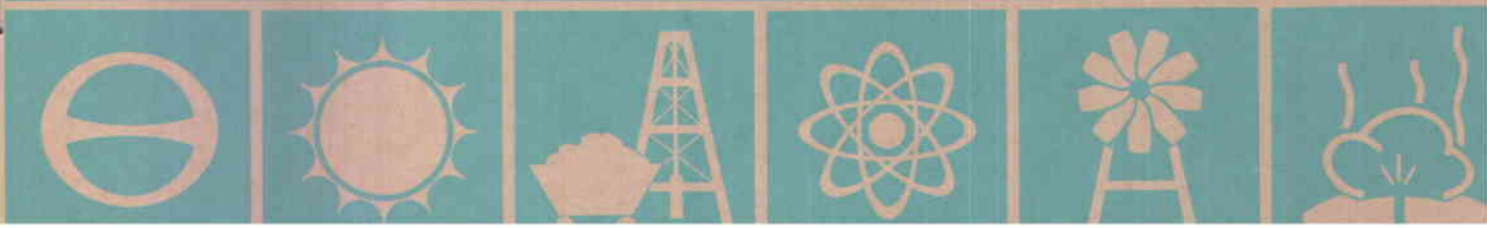

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THE CREDIBILITY OF COST ESTIMATES FOR MASS-PRODUCED HELIOSTATS

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ABSTRACT

Five analysis approaches are applied to the McDonnell Douglas second generation prototype heliostat capital cost estimates in an attempt either to justify or to discredit them. The estimates are not discredited by any of these approaches, so they are accepted as credible. A range of credible costs is calculated based on the analyses. This range is \$100/m^2/R to \$60/m^2/R for unit number 350,000 at 25,000/year production rate.

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THE CREDIBILITY OF COST ESTIMATES FOR MASS-PRODUCED HELIOSTATS

Introduction and Summary

The cost of heliostats is a critical issue in the economic competitiveness of central receiver solar thermal power systems. Cost estimates have been generated for four different mass-producible heliostats at various production rates, and those estimates fell in a range which make central receiver systems competitive with more conventional systems for electrical generation in some future scenarios. The critical question is, therefore, are the cost estimates correct?

The cost estimates can only be proven correct by setting up mass production facilities and selling heliostats in a competitive market for several years. However, the estimates can be evaluated and tested in an attempt to find serious inconsistencies that would discredit them. If there are no inconsistencies and the estimates are reasonable relative to each other and relative to other mass produced items, that tends to raise the level of confidence.

The purpose of this document is to evaluate the credibility of the estimates with particular attention to glass heliostats. Several points of view are adopted, as follows.

1. Evaluation of the estimates for level of detail, completeness, and consistency. This is the most important evaluation because it leads to confidence in the basic data.

2. Comparison of the heliostat cost per pound with the cost per pound of commonly manufactured items.

3. Association of the cost reductions in each subsystem with specific design changes between the Central Receiver Test Facility (CRTF), pilot plant (PDR), and second generation mass producible heliostat designs.

4. Examination of the breakdown between labor and material and the relative accuracy of estimating each.

5. Determination whether the actual price paid for CRTF heliostats and the estimated costs of the PDR and second generation designs fall along an experience curve typical of mass produced items.

The principal result is that the second generation prototype cost estimates cannot be discredited by any of these tests. In addition, four of these viewpoints lead to rough bounds on the credible cost of the best of the four designs. The tightest of these bounds, given in Table 3, is the one resulting from assumed probable errors in the material and labor estimates. That bound shows a probable range of $60/m^2/R[†] to $100/m^2/R for unit number 350 000 at 25K/year production.

General Evaluation of Second Generation Estimates

Four contractors recently prepared preliminary designs and cost estimates for second generation prototype heliostat designs.[1-4] These designs are summarized, compared, and evaluated in Reference 5. The best design was the glass McDonnell Douglas (MDAC) design, on the basis of lowest projected lifecycle cost, most mature design and cost estimates, and lowest technical risk. This design represents the third in a series of glass and steel inverted stow heliostats; the other two are the Martin Marietta design[6] installed at the Central Receiver Test Facility (CRTF) at Sandia Laboratories, Albuquerque, and the MDAC design[7] proposed for the 10 MW pilot plant at Barstow, California (labeled "PDR" design below). Selected characteristics of these three designs are presented in Table 1.

The first step in the evaluation summarized by Reference 5 was to put the data from all contractors in a consistent framework. The detailed backup sheets in References 1-4 were supplemented by discussion with the cost estimators at each firm to ensure that each estimate included the same items under the same headings. Missing items were filled in from the other contractors' estimates and the percent fee and contingency were set equal for all. Individdual line item estimates varied considerably because of differences in the designs. For instance, GE drives and mirrors cost an order of magnitude less than MDAC drives and mirrors, but this corresponds to a real design difference. The GE drives and mirror are protected by an enclosure from loads that the unprotected MDAC design must withstand. Each significant difference in the cost estimates was analyzed, and a design difference was identified in all cases.

The McDonnell Douglas estimate is quite complete and detailed, including every nut and bolt in the design. This is hardly surprising, since the MDAC second generation design evolved from the PDR design through a series of detailed tradeoff studies. The computerized cost data base also evolved in an updating process, so one would expect the relatively detailed result.

In the chemical process industry, a cost estimate with this level of detail would be considered a "Definitive Project Control" estimate, with probable error bounds variously given as ±10 percent at 95 percent confidence[8] or ±6 percent at unspecified confidence.[9] These bounds are tight because of many decades of experience and sharing of cost information in the process industry--a totally different situation from the fledgling heliostat industry. In addition, these error bounds are for plants to be built in the near future,

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[†] Throughout this report, $/m^2/R means mid-1978 dollars divided by mirror area in m^2, divided by clean reflectivity to roughly normalize performance. The appropriate factors are in Table 1.

Table 1. Selected Characteristics of Three Glass Heliostat Designs.

	Mirror area m^2	Clean Reflectivity	Weight, lb (excluding foundation)	Weight of foundation lb	Total installed recurring cost† 1978$/heliostat	Production run, no. of heliostats	No. of heliostats in field
Martin Marietta design installed at Central Receiver Test Facility (CRTF)[6]	37	0.83	5500	32 000	26 300	222	222 ($5MW_t$)
McDonnell Douglas design for pilot plant (PDR)[7]	38	0.91	3520	9700	10 600	1760	1760 ($10MW_e$)
McDonnell Douglas second generation prototype design (second generation)[3]	49	0.92- 0.95	4041	12 600	3600	25 000/yr	16 900 ($100\ MW_e$)

†Cost includes heliostat, foundation, field wiring and control, initial spares, maintenance equipment, and for PDR and second generation estimates, 10% contingency and 8% fee. CRTF figures are average price paid, including about 6.5% fee.

rather than manufactured items after ten years of production. Considering the uncertainties, the intuitive bounds on heliostat cost estimates are certainly larger, perhaps two to three times wider than the normal process industry bounds, i.e., ±30 percent. These bounds correspond to $\$55/m^2/R$ to $\$105/m^2/R$ for the 350 000th unit.

Comparison with Other Items by $/lb

When products are produced in large volume from the same materials, the wholesale cost per unit weight tends to be similar for items of similar complexity. This is because the cost per unit weight of raw material is the same and the value added during manufacture (by machine and labor) is similar. The items may have different lifetimes, reliabilities, duty cycles, uses, etc., but these factors will not affect the cost per pound unless they also affect the design or manufacturing complexity or the choice of material.

Figure 1 shows the estimated wholesale cost per pound (in 1978 dollars) for a variety of common items, as well as the estimated cost per heliostat divided by weight at 250 000/year production. For this figure only, the heliostat costs and weights do not include land, lightning protection, field wiring, the concrete part of the foundation, installation, spares, facilities and equipment, packaging and transport, etc. The comparison is flawed in several ways, including:

1. Except for heliostats, the production volumes are different and unknown, and most items have been produced by competing firms for many years.
2. The price per pound of many of the consumer items was estimated from retail prices and shipping weights given in Sears catalog, using:

    a) wholesale cost $\cong$ 0.65 (retail price)

    b) item weight $\cong$ 0.85 (shipping weight)

    Relation a) is supported by the fact that cost of goods sold is roughly equal to 65 percent of income according to Sears annual report. Relation b) is an estimate from the author's experience. The "Kelly Blue Book" was used for the automotive items.
3. The abscissa is a qualitative judgment of complexity.
4. None of the comparison items has a similar ratio of glass and steel weights.

With these limitations in mind, Figure 1 can be used to aid one's intuition on the reasonableness of the high production heliostat cost estimates.

The second generation heliostats do fit into the appropriate region on Figure 1, considering the materials and processes involved. The plastic GE enclosed design is about $2/lb, along with other molded and extruded plastic items. The Boeing price of $1/lb is lower than that of all plastic items but in line with fabricated metal items. This is reasonable since the weight of plastic is small compared to the weight of steel and aluminum in this design. The MDAC and Solaramics designs are at roughly $0.5/lb, in line with relatively

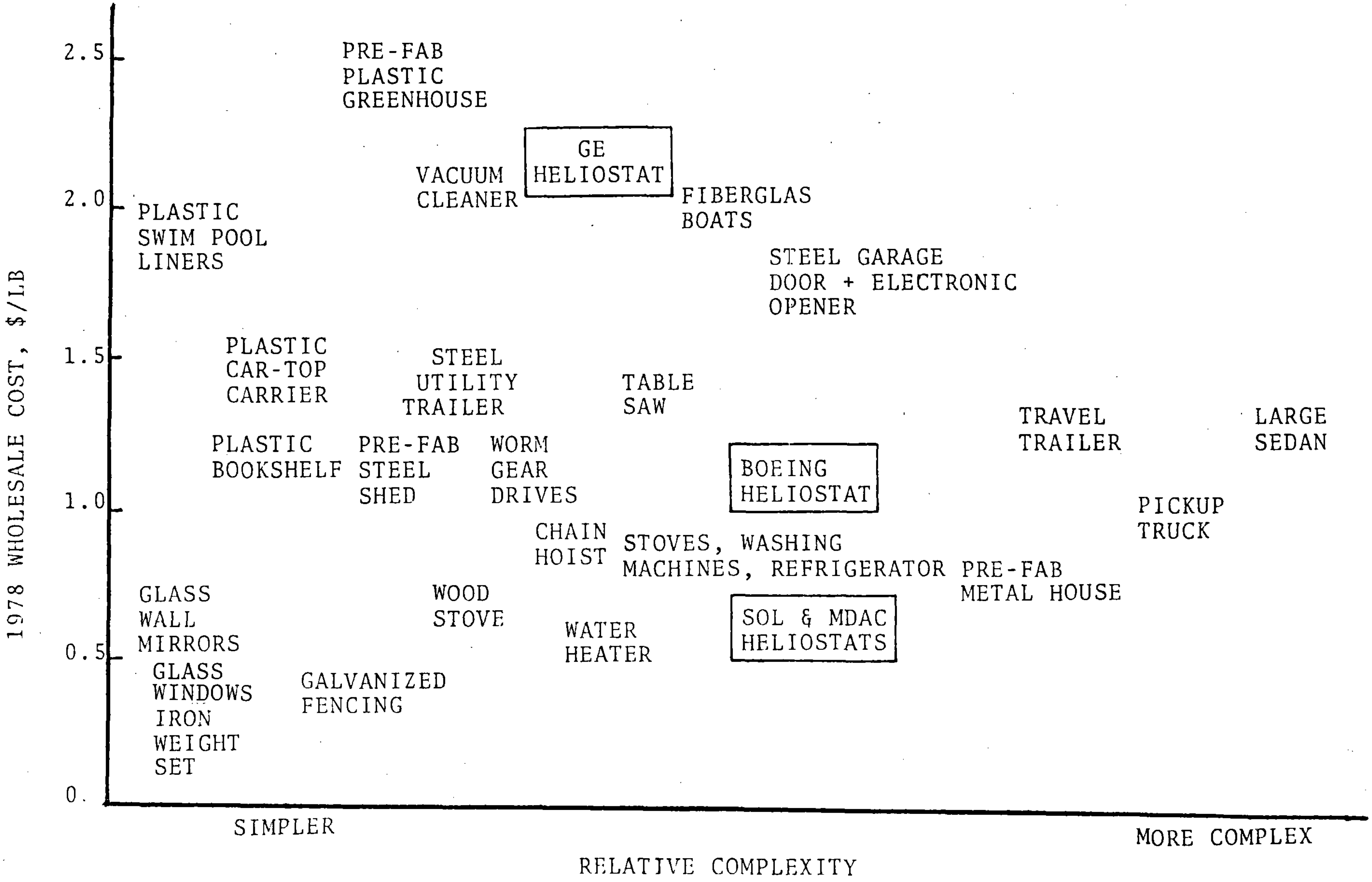

Figure 1. Comparative Wholesale Costs for Mass-Produced Items.

simple items using steel and glass. Note that almost half of the weight of the MDAC design is the glass, but the glass cost plus 10 percent contingency is only \$420 (from data supplied by Corning and ASG - see pg. H-65 in Reference 3). Therefore, the figure \$0.5/lb really consists of \$0.25/lb for the glass and \$0.70/lb for the steel portions of the design, and Figure 1 shows that these are reasonable.

It is possible to bound the cost of the glass and steel portion of the heliostat by considering the credible range in dollars per pound. It is not likely that this heliostat could ever be produced for \$0.25/lb because its price per pound would then be comparable to simpler items made in large quantities, such as window glass, weight sets, fencing wire, etc. Similarly, \$1.00/lb is an overestimate, because heliostats are considerably simpler than automobiles and pickup trucks and roughly half of heliostat weight is relatively cheap glass. This establishes worst-case limits of \$1000 to \$4000 for the steel and glass portions of the design, based on the MDAC weight of 4000 pounds.

If the estimated costs for foundations, wiring, installation, lightning protection, spares, facilities and equipment, packaging and transport are added to these worst-case limits, bounds on the installed heliostat cost in high volume production can be obtained. Where the cost of the above items varies with production rate, the highest production rate estimate (10^6/year) provided by MDAC is used. The result is the range \$40/m^2/R to \$110/m^2/R, which should hold for all glass and steel designs of similar complexity and weight. The MDAC estimate at 10^6/year production rate is \$61/m^2/R, which is somewhat below the middle of this range.

It is important to note that this analysis has <u>not</u> produced a lower bound on the eventual cost of glass and steel heliostats. Changes in design could reduce the weight and complexity or result in substitution of cheaper materials. For example, the cost of the pedestal could possibly be reduced by substituting concrete for steel. In addition, only half of the lower bound is the cost of steel and glass; the remainder is the sum of estimated costs for the items listed in the preceding paragraph. Those costs can also be reduced, for instance, reducing installation by making a one-piece, pre-cast foundation and pedestal or by innovations in wiring. However, the mass-produced cost of the MDAC design (or similar) is likely to be in the specified range regardless of production rate and duration unless there <u>are</u> changes in design or installation scenario.

Cost Breakdown by Heliostat Subsystem

The cost breakdown by subsystem for CRTF,[6] PDR,[7] and second generation[3] heliostats can be used to identify the magnitude and the specific area of projected cost reduction (see Figure 2). (The CRTF costs are actual; the others are estimates.) These cost reductions are caused by four major factors:

1. Field and batch costs decrease with increasing number of heliostats in the field or production run (see Table 1), when expressed on a per-heliostat basis as is done here.

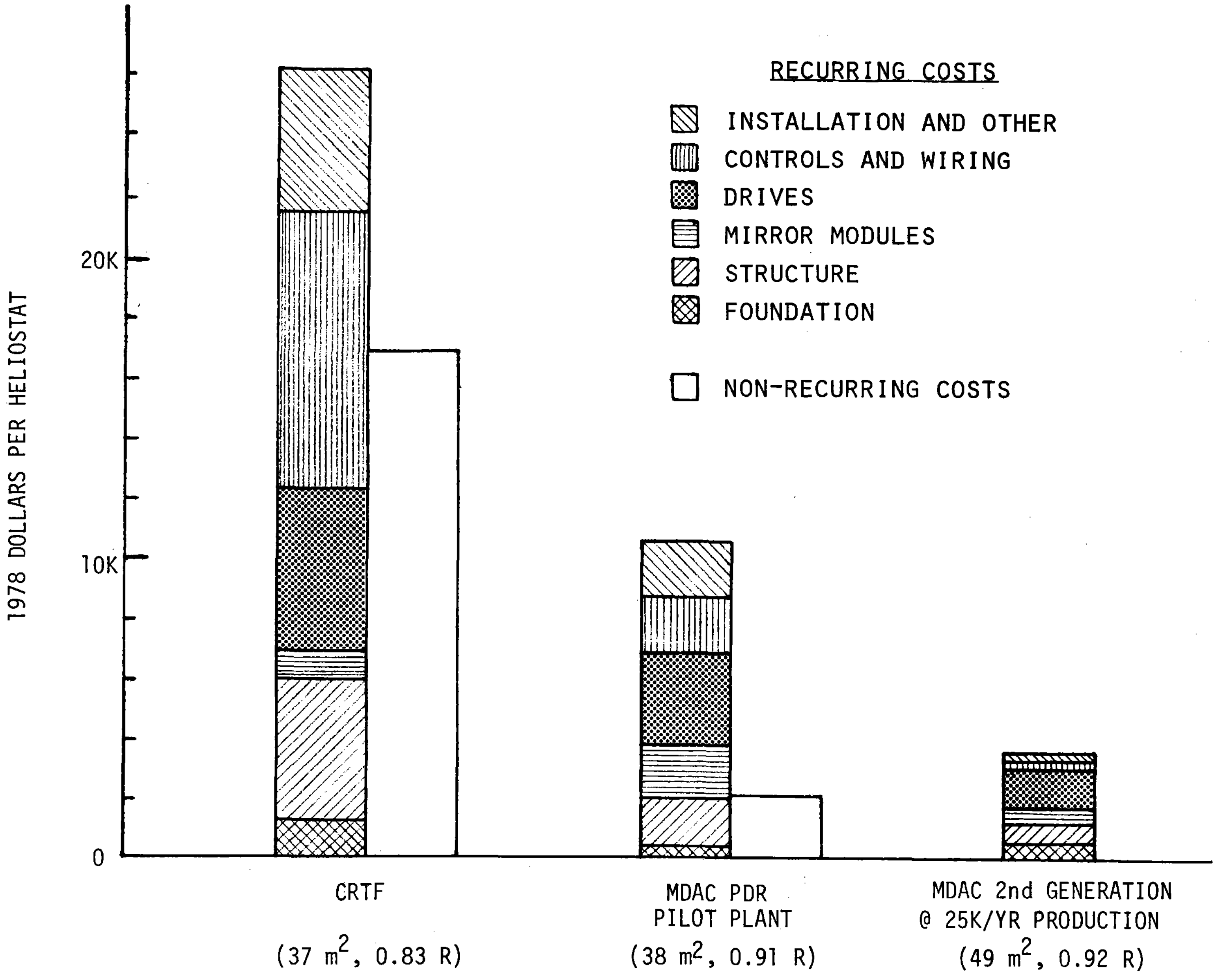

Figure 2. Cost Breakdown for Three Heliostat Designs.

2. Some costs are dependent on the installation or production scenario--they change by assumption.

3. Design, manufacturing process, and production volume all affect manufacturing cost.

4. Position on the experience curve may affect all costs, as discussed in detail in the experience curve section below. It is worth noting here that experience curve effects include all changes in (1)-(3) plus labor learning (including management, engineering, and production and installation). The combined effect (on an 85 percent curve) would predict a factor of four reduction in cost between PDR and second generation, and a factor of two reduction between CRTF and PDR designs. Since the experience effect applies to all costs, it will not be discussed further in this section. Instead, an attempt will be made to identify those factors (1)-(3) which apply to specific subsystem changes. Examination of each subsystem change cannot validate the magnitude of the change, but it can hopefully identify any unsupported changes.

Non-recurring cost is affected by both the first and second factors above. The pilot plant has 1760 heliostats compared to 222 at CRTF, so the cost of field design, production tooling, etc. is roughly an order of magnitude smaller per pilot plant heliostat. Non-recurring costs are eliminated from the second generation cost estimate, under the assumption that the estimate is after ten years of production and all non-recurring costs have been charged to previous production years.

Of the recurring costs, the most conspicuous reductions occur in the categories Control and Wiring and Installation and Other. These categories include some per-field costs (such as installation equipment and crew, field control computer, etc.) which decrease on a per-heliostat basis by an order of magnitude between CRTF and PDR and again between PDR and second generation. The other major sources of cost reduction in these categories are: (a) redesign to nearly eliminate installation and calibration labor, (b) change in wiring design and installation procedure to avoid labor-intensive operations, (c) volume production economies in the electronics which reduce the cost of heliostat control plus encoders, and (d) labor learning (these categories include much of the total labor cost).

The categories Drives, Mirror Modules, and Structure contain the major costs of the PDR and second generation heliostats. The cost of these subsystems decreased by about 40 percent as did their weight between CRTF and the pilot plant. Here the major cost reduction comes from redesign that reduces weight. Not all individual costs go down; the weight and cost of the mirror modules in the pilot plant design are higher than CRTF because a glass/foam/steel composite is used instead of laminated glass.

The cost reduction between PDR and second generation does not correspond to a weight reduction, however. The weight of the second generation design is 15 percent higher[†] than PDR, which would result in a cost increase if nothing else changed, so it is necessary to examine each change in detail.

[†] The absolute weight increased 15 percent but the weight per unit reflective area decreased by 12 percent. The second generation design is more efficient in its use of material.

The second generation drives are simpler in design than the PDR drives, and their weight is 6 percent lower even though they carry greater loads. Thus the material cost of the drives, which are the most expensive parts in the heliostat, should be more than 6 percent lower in the improved design.

The second generation mirror panels (laminated glass) are also simpler than the PDR panels (glass/foam/steel sandwich). The materials cost is 42 percent lower even though the weight is 41 percent higher and the area is 31 percent greater because structural backup is provided by relatively cheap glass rather than styrofoam and steel. The glass is bought in large quantity (43 million pounds per year at 25 000 heliostats per year) so quantity discounts will apply. The glass laminating process is also well known and inherently easier to automate, so manufacturing costs should be substantially lower.

The second generation steel structure is only 4 percent heavier because of redesign for more efficient use of material. In addition, the quantities of steel are large enough (42 million pounds per year) that attractive quantity discounts will be available.

All three categories are affected by the difference in production scenario between PDR and second generation. The pilot plant production is essentially a job-shop operation with limited tooling, producing a relatively small number of units of a new product. The second generation estimate assumes constant production in a dedicated facility, with all necessary tooling for appropriately automated manufacture and assembly, and all startup costs and production snags have been eliminated in ten years of prior production. The combined effect of improved manufacturing and ten years of labor learning is reduction of second generation labor cost to one-tenth the PDR labor cost in these categories. The combined effect of redesign and volume purchasing as detailed in the previous paragraphs is reduction of material and purchased parts to one-half of the PDR cost. Taken together, these changes adequately support the 64 percent reduction in the cost of drives, mirrors, and structure.

The foundation design changed dramatically in the three design generations. The weight of concrete and steel dropped from 32 000 pounds at STTF to 9750 pounds at pilot plant, then increased to 12 600 pounds to handle the greater mirror area of the second generation design. These weights are in the ratios 3.3:1:1.3, and the costs are similarly in the ratios 2.8:1:1.5. The close agreement between weight and cost is typical of reinforced concrete construction.

Cost Breakdown by Material and Labor

Figure 3 shows the breakdown of labor and materials for the three designs. Materials and purchased parts are the major costs in all cases--as much as 77 percent in the production design. This is typical of high volume production, but the high parts and material component (73 percent) in the CRTF design is somewhat surprising. The situation is caused by expensive purchased parts, in particular the drives, encoders, and heliostat controllers. The labor component does not decrease as much as material between CRTF and pilot plant, because there is no major difference in assembly, installation, and fabrication scenarios for those designs. There are major differences between pilot

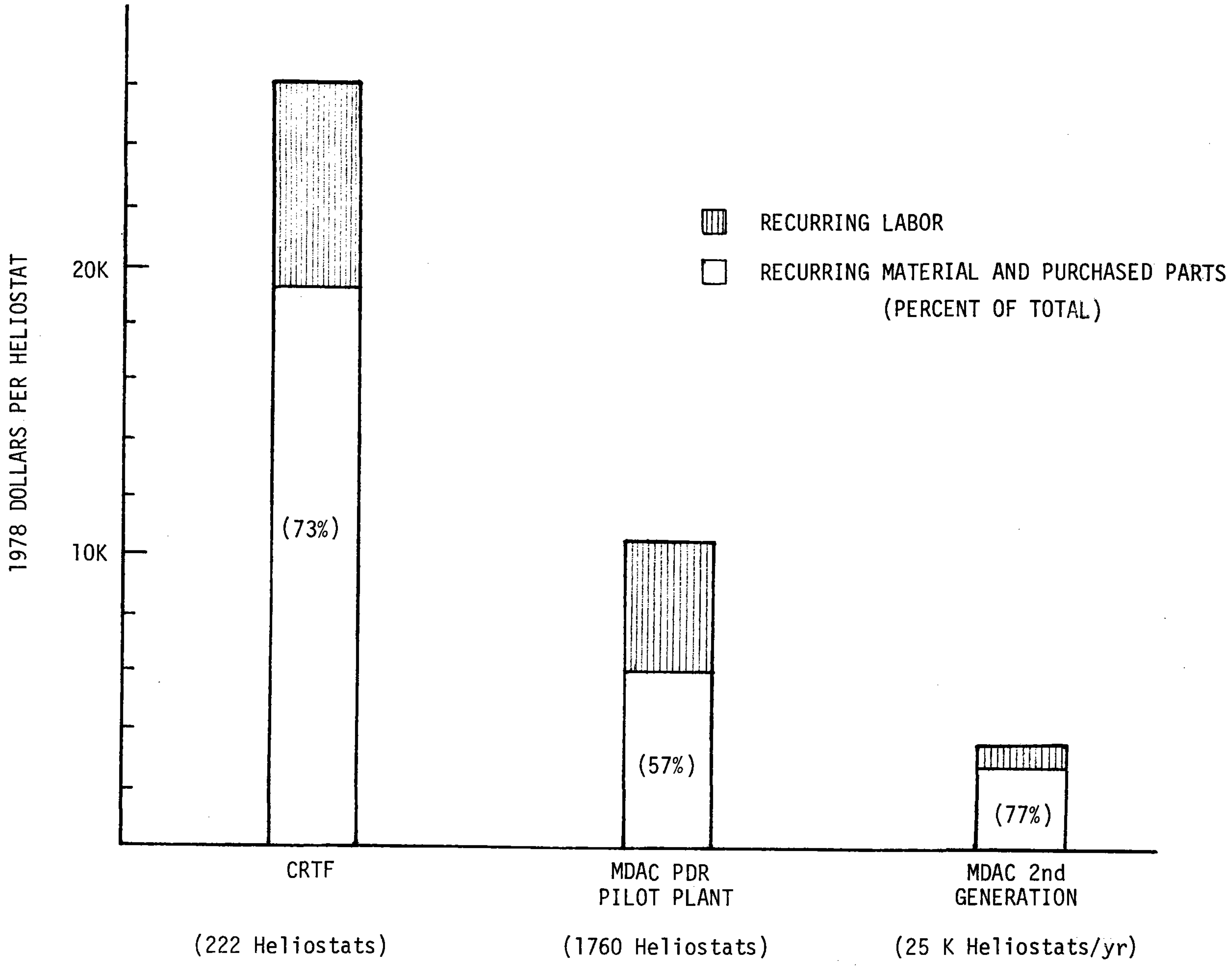

Figure 3. Material and Labor Costs for Three Heliostat Designs.

plant and second generation: installation is dramatically streamlined, field assembly is virtually eliminated, and automated equipment is used where appropriate. Consequently, the labor cost decreases more rapidly than material between pilot plant and second generation designs.

It is significant that materials account for 77 percent of the latest cost estimates, because the amount of material in a product and the current cost of that material at various volumes can be estimated more accurately than the required manpower to build and install the new product. This was taken into account by the cost estimators at McDonnell Douglas; their bottom line estimates contained a 20 percent visibility (contingency) for labor but only 10 percent for material. Many sensitivities can be done, for example, assume that the uncertainty on materials is twice as much (20 percent) as was assumed by MDAC. This implies that the actual materials cost would be in the range of 30 percent less to 10 percent more than the bottom line materials estimate from MDAC. Similarly, if there is a factor of two uncertainty in labor, the labor cost could be as much as 80 percent more or as much as 70 percent less. (The reader should note that the emphasis here is on providing an upper bound.) The superimposed effect on total cost might then roughly be given by:

$$\text{upper bound} = [(0.23 \cdot 80)^2 + (0.77 \cdot 10)^2]^{1/2} = +20 \text{ percent}$$

$$\text{lower bound} = [(0.23 \cdot 70)^2 + (0.77 \cdot 30)^2]^{1/2} = -28 \text{ percent.}$$

The probable range for the MDAC second generation design in 25K/year production is therefore $\$57/\text{m}^2/\text{R}$ - $\$96/\text{m}^2/\text{R}$ for unit number 350 000. The MDAC estimate ($\$80/\text{m}^2/\text{R}$) is somewhat above the midpoint of this range.

It is important to note what has been included in these bounds. All capital costs of the collector field (plus 8 percent fee) are included, except land. The estimated bounds were chosen large enough to account for unknown changes over ten years of production. But the range should be somewhat larger for the MDAC estimates at other production rates, because they were obtained partly by projection along assumed learning curves and by changing the production scenario from the carefully-analyzed base case (25K/year). The percentage range should not be applied to the capital portion of the annual cost in Reference 5 because land, heliostat performance and field efficiency, interest rates, tax, depreciation, and utility financial structure are additional variables in those estimates.

Experience Curve Analysis

The final check is to examine the historical development of heliostat prices and cost estimates to determine if the projections fall on a typical experience curve. The CRTF, PDR, and second generation designs can be considered developmental stages of the same product - namely a means for providing a glass reflective surface with tracking and control. During the production of any such product, cost and price (in constant dollars) normally decrease by a constant percentage as the number of units produced doubles. If a product follows an 80 percent experience curve, the 200th unit cost is 80 percent of the 100th unit cost and the 400th unit cost is 80 percent of the 200th, etc. This cost reduction results from several factors, including labor learning, reduction in raw material costs due to supplier experience plus higher volume purchasing (and sometimes vertical integration), capital investment in larger, more automated plants, and innovation in design, manufacture, and marketing.

The magnitude of cost reduction for a variety of items is shown in Table 2. Typical numbers are 80-90 percent on unit labor and 70-90 percent on raw materials, leading to experience effects on total cost or price of 70-90 percent. Individual items may deviate from these ranges; for instance, the price of germanium diodes dropped at a 45 percent rate over 3 billion units, and the wholesale cost of gas ranges dropped at a 60 percent rate for 27 million units made between 1952 and 1967.[10] Experience curves can be disrupted by a variety of factors, such as consumer demand for improved performance[12] and government antitrust actions (see Reference 10, pg. 49).

One would expect to see a typical experience effect for heliostats, if cost is expressed in constant dollars divided by mirror area and reflectivity to roughly account for size and performance changes. Of course there is very little available experience on heliostat costs, but the actual costs at CRTF can be compared with estimated costs for the later designs to see if they fall along a typical (i.e., 70-90 percent) experience curve. Figure 4 shows that the estimates do indeed fall in the credible range, within a band of 85 percent curves. The horizontal lines on Figure 4 are drawn at the lot average cost for the early production; within each lot the cost also decreases, but data on that effect are not available. Note that all of the factors (redesign, volume increase, etc.) that contribute to experience curves are present in the estimates in Figure 4.

The curves in Figure 4 can be used to provide bounds on the 10 000th unit (typical of first commercial plant) and the 350 000th unit (typical of the 20th 100 MW commercial plant). These results are bounds of 120-310 $\$/m^2/R$ for the 10 000th and 60-140 $\$/m^2/R$ for the 350 000th unit. Note that Table 2 suggests that these numbers could be high.

Conclusions

The McDonnell Douglas second generation heliostat cost estimates have been examined from the five viewpoints listed in the introduction--none of these viewpoints can be used to discredit the estimates. Four of these approaches lead to estimated ranges within which a cost estimate would be accepted, as summarized in Table 3. The often-stated DOE goal of $\$72/m^2/R$ is also well within the credible cost ranges for the 350 000th unit of this design.

Finally, the cost breakdowns in Figures 2 and 3 show where future cost savings are most likely. The only dominant category in the second generation cost estimate in Figure 2 is Drives. If azimuth and elevation/stow drives were separate categories, there would be no dominant category. This suggests that there is limited cost reduction potential in any one part of the design, so major cost reduction can only be achieved by cutting costs in all parts simultaneously. Figure 3 also shows that major cost reduction must come from material and purchased parts, since labor has little leverage on total cost. Putting these facts together, the most promising areas to look for cost savings are the high material categories Drives, Mirror Modulbs, Structure and Foundation.

Table 2. Experience Curve Data

Item	Average Slope	Comments on Curves	Reference
Black and white TV, wholesale price	80%	92% to 30 M units (1953) 70% to 140 M units (1968)	10, p. 92
Free-standing electric range, average price	80%	97% to 17 M units (1957) 65% to 30 M units (1967)	10, p. 95
Free-standing gas range, wholesale price	70%	Flat to 48 M units (1952) 60% to 76 M units (1967)	10, p. 94
Model T Ford, list price	85%	14 M units produced 1908-1926	12, p. 111
Turbine generator sets, direct cost/MW	90%	1946-1963 production data from GE	11, pamphlet II
Electronic components	60-80%	Transistors, diodes, integrated circuits	10, pp. 70-75
Electric power, US utilities, \$/kwh	80%	55% to 10^{12} kwh (1945) 80% to 10^{13} kwh (1968)	10, p. 99
Labor unit cost			
machine-paced	90%	Consensus of many sources in many industries	12-15
worker-paced	80%		
Raw material unit cost			
metals	80-90%	(Al, Mg, Ti) data to 1968	10, pp. 86, 88, 90
polymers	70-90%	(polyethylene, polypropylene, polystyrene, polyvinyl chloride)	10, pp. 81-85
crushed limestone	80%	Data 1929 to 1971	11, pamphlet V

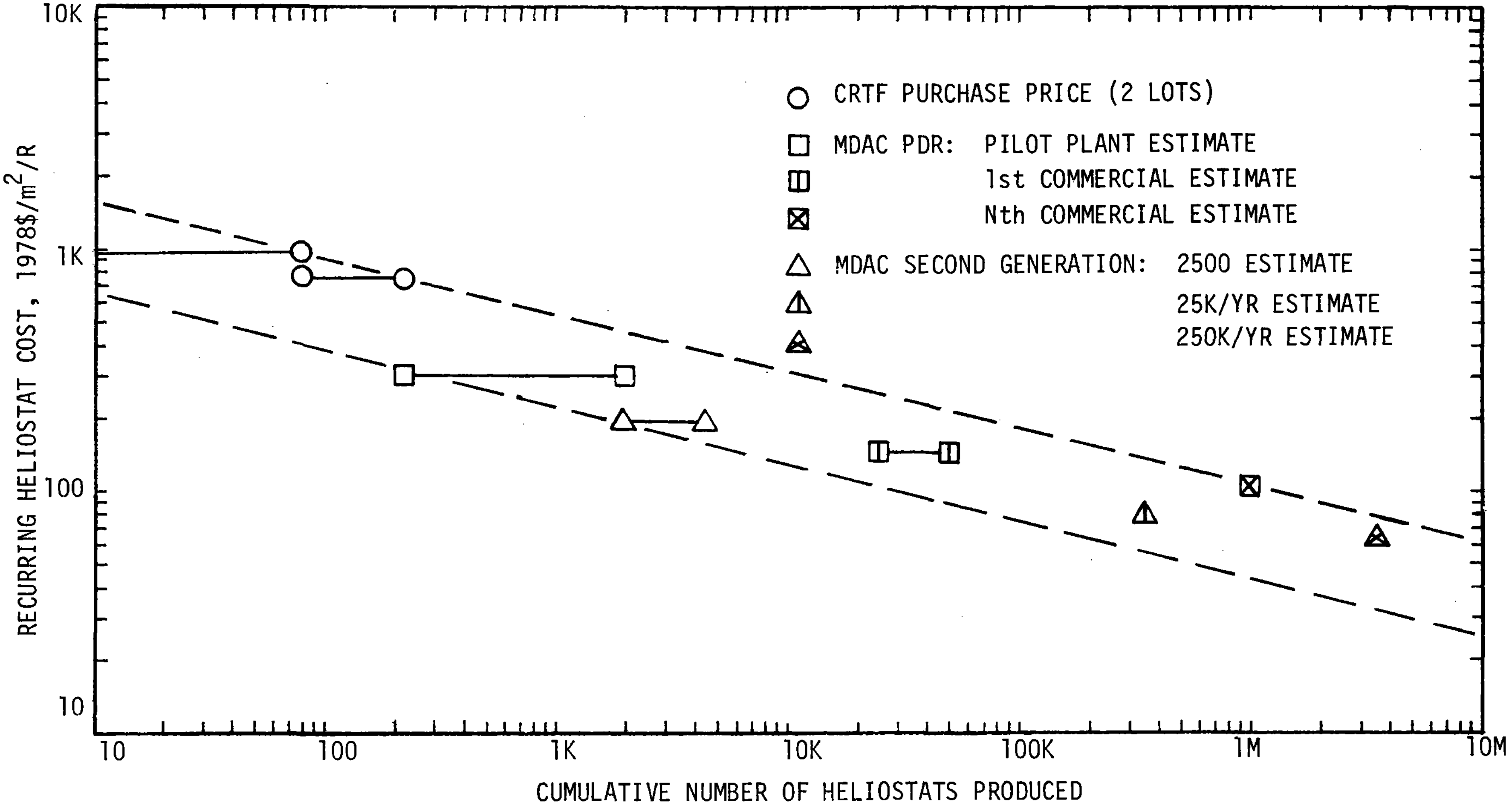

Figure 4. The Trend Line for Heliostat Cost Estimates. All estimates are for installed heliostats including foundations, wiring, field control, 8% fee and ∿10% contingency. The dashed lines are 85% experience curves.

Table 3. Summary of Credible Cost Estimate Ranges for the McDonnell Douglas Second Generation Prototype Heliostat.

Cost Range, 1978$/m^2/R	Applies to:	Basis of Estimating
(a) 55 - 105	350 000th unit at 25K/yr production	Intuitive range, based on level of detail and completeness of MDAC estimates.
(b) 40 - 110	Unspecified (but large) unit number and production volume	Credible range of $/lb for glass and steel, plus all other costs from MDAC's 1M/yr estimate.
(c) 60 - 100	350 000th unit at 25K/yr production	Intuitive range as in (a), considering material/labor breakdown and equally probable errors in material and labor estimates.
(d) 60 - 140	350 000th unit, unspecified production rate	85% experience curve applied from CRTF costs (see Figure 4).
(e) 120 - 310	10 000th unit, unspecified production rate	85% experience curve applied from CRTF costs (see Figure 4).

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