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A Strategy for Heliostat Commercialization

L. D. Brandt

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A STRATEGY FOR HELIOSTAT COMMERCIALIZATION*

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ABSTRACT

Commercial viability of the solar central receiver technology depends in part on the availability of low cost, mass produced heliostats. This study recommends a path for developing an independent industry capable of producing such heliostats. Conclusions are drawn largely from discussions with firms currently involved in the heliostat research and development program. Evolution of heliostat costs during commercialization and factors that influence near term government demonstration programs are reviewed.

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A STRATEGY FOR HELIOSTAT COMMERCIALIZATION

Summary

Availability of low cost heliostats is a critical factor in making the solar central receiver technology an economically competitive energy option for a variety of electrical generation and industrial process heat applications. Development of a commercial mass production capability for heliostats could cause a significant reduction in heliostat cost. This study identifies a commercialization path from the current government supported heliostat R&D program to establishment of a private commercial market. Study conclusions have been drawn largely from discussions with potential heliostat suppliers.

Heliostat suppliers indicated that the major tasks to be accomplished during commercialization are: 1) expansion of production rates to exploit economies of scale, 2) development of effective manufacturing processes and 3) continued design evolution to make heliostats more producible. One commercialization path that achieves these goals involves several competing suppliers providing heliostats at increasing production rates over the next decade. The stages of production envisioned by the suppliers are: 1) <u>intermediate production</u> of 2000-5000 heliostats annually for approximately 3 years, followed by 2) <u>initial mass production</u> of 15,000-30,000 heliostats annually for approximately 5 years, leading finally to 3) <u>mature mass production</u>. (Note that each 1000 heliostats produced corresponds to an installed capacity of 6-7 MW_e with a 0.5 capacity factor in an electrical application [2]). Over the commercialization

period, the cost of heliostats is expected to decline and the processing experience necessary for high level mass production will be acquired.

Programs supported in part by government funding will provide the only significant demands for heliostats in the near term. The upcoming repowering/retrofit program, if properly structured, provides an opportunity to meet the goals of the intermediate production phase of heliostat commercialization.

I. Introduction

Recent studies (e.g.[1]) have shown that the solar central receiver technology has the potential for competing with coal and oil fired plants over a wide range of thermal and electrical generation applications. There are currently several barriers to a private commercial market for central receiver systems. One is the unavailability of low cost central receiver systems. A second is the lack of sufficient performance and reliability data to convince potential users of the utility of the central receiver concept. This study is a portion of an overall program review [2] intended to identify a commercialization path that overcomes these barriers.

The goal of the commercialization process is development of an independent market for central receiver systems that requires no unusual government support or intervention. The two components of a market are users who understand and have economically viable applications of the technology and suppliers who can sell central receiver systems at competitive costs. Development of a user community depends, in part, on information dissemination and a properly managed demonstration program. A companion study [3] discusses specific program recommendations obtained from one group of potential users, the electric utilities.

This study focuses on the development of production capability by suppliers of the heliostats employed in central receiver systems. Creation of an industry to provide low cost heliostats is the most significant task in supplier commercialization. Major resource inputs in the forms of process development, production experience and capital investments in mass production facilities need to be made if heliostat cost and performance goals are to be realized. Achieving the economies of mass production to meet cost goals is particularly important because heliostats comprise a major fraction of the system cost. The other components of the central receiver system do not face the same commercialization barrier as heliostats. Although design and production issues must be resolved, particularly for the receiver, the existing industrial base and related production experience should make commercialization a less demanding process. For the nonsolar components (e.g. towers, turbine/generators, etc.), production capabilities already exist to support foreseeable needs.

A primary requirement for heliostat commercialization is the attraction of a potential market to suppliers. In response to market growth, a variety of commercialization activities beyond research and development would be undertaken. These activities include further production-oriented design iteration, process development and production learning. The goal of this study is to identify and understand the required supplier tasks during the commercialization period. This information is necessary to insure that government decisions affecting heliostat development and production will take supplier needs and constraints into account.

This report begins by reviewing the sources of information employed in the study. Then the goals of commercialization followed by a recommended commercialization path are presented. In the near term, government programs will dominate the market for heliostats. Thus a discussion of implications of the commercialization plan for government decisions is presented. Finally, a review of the impacts of an accelerated program is included.

II. Information Sources on Heliostat Commercialization

The major inputs for the conclusions reached in this study were provided by contractors presently involved in heliostat development. In order to obtain a range of views concerning the commercialization process, discussions were held with the following firms:

General Electric
Martin Marietta Aerospace
McDonnell Douglas Astronautics
Northrup
Westinghouse

The heliostat manufacturing studies sponsored by SERI and performed by General Motors (Transportation Systems Division) [4] and Battelle, Pacific Northwest Laboratory [5,6] were also useful in estimating capital costs of manufacturing facilities and other heliostat production costs.

Meetings with the potential suppliers listed above were intended to elicit their views on a range of issues including the readiness of the glass/metal design for production, activities that must occur before mass production could begin, and the supplier's own view of how the commercialization process should be carried out. Because of the diversity of the issues discussed, representatives of a range of corporate functions were invited to the meetings. These included manufacturing personnel, as well as corporate planning, marketing and financial staff, and the management associated with current heliostat development. In order to introduce the issues, a set of preliminary questions was sent to each supplier prior to the meetings. A copy of these questions is included in Appendix A. In many cases the questions did not closely represent the particular concerns of the attendees. In these cases, the discussion departed significantly from the structure outlined in the questions. The results presented in this report will also deviate from the question structure in order to emphasize those aspects of commercialization that were most important to the suppliers.

There was a surprising consensus among the suppliers concerning the major requirements for commercialization. There were, of course, differences over more detailed issues such as production rates, costs and make/buy decisions for particular production scenarios. However, the overall view of how the process should proceed was relatively consistent among all potential suppliers.

III. Goals of the Commercialization Process

Heliostat suppliers believe that a successful commercialization program will serve several vital functions. The most important of these are listed below.

1. Investment in and operation of mass production facilities to exploit economies of scale.
2. Development of production and installation processes.
3. Design evolution resulting from production experience to develop a more cost effective and producible heliostat.

Accomplishment of these goals during the commercialization period will encourage formation of a viable private heliostat industry. Heliostat prices will continue to decline as these objectives are met. Each of these goals is reviewed in more detail below.

1. Investment in and Operation of Mass Production Facilities

Previous production studies (e.g. [4], [5], [6], [7]) have shown that increasing the scale of production (production rate) and operating a dedicated production facility for extended periods of time are the most important factors in heliostat cost reduction. Increasing the scale of production justifies increased automation which in turn reduces costs. Higher production rates may also alter make/buy decisions so more components are made by the heliostat supplier rather than purchased. This increased factory integration insures the supply of critical manufactured components as well as reducing costs. Operating the production facility for an extended period is important so fixed costs can be distributed over many heliostats.

The effect of increased production scale on heliostat cost is shown schematically in Figure 1. Studies have indicated that increasing production rates to several hundred thousand heliostats annually will result in heliostat costs below $\$100/m^2$. More detailed cost projections are discussed in Section V.

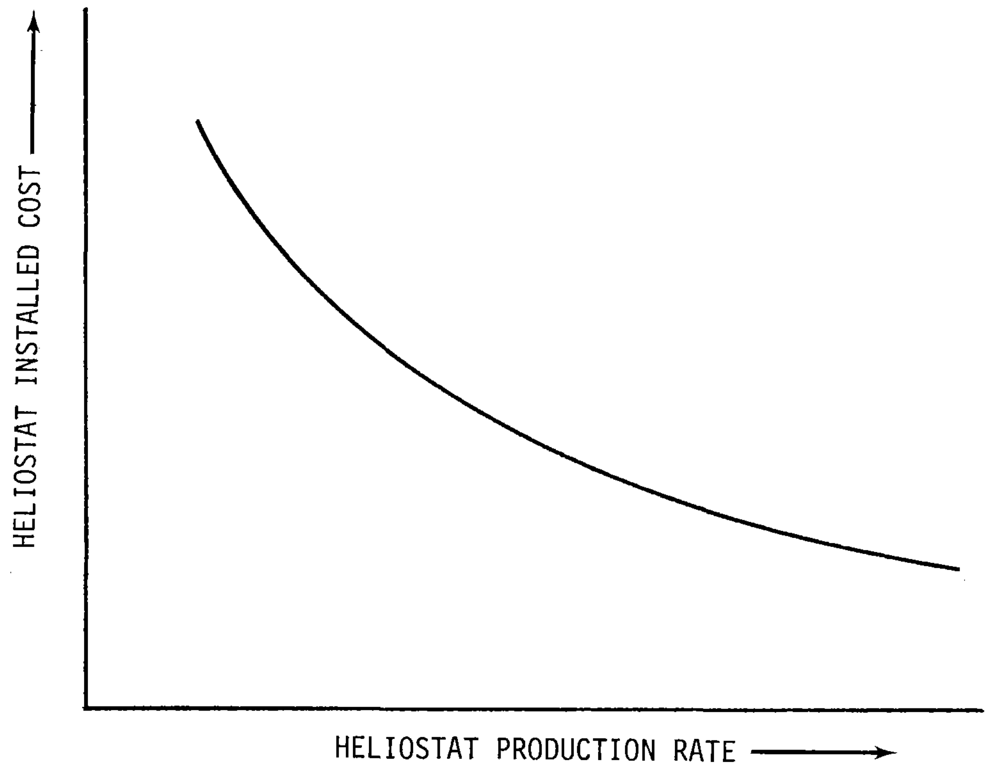

Figure 1. Economies of Scale in Heliostat Production

Discussions with heliostat suppliers have identified important caveats that apply to the use of curves such as shown in Figure 1. If viewed in isolation, Figure 1 would suggest that the best heliostat commercialization strategy is to proceed to very high production rates as soon as possible. Doing so, however, would force an early commitment to a particular heliostat design and a shortened period for development of mass production processes. The choice of a production plan must balance the need for early high level production to exploit economies of scale with the need to perform necessary process development and arrive at a production heliostat design. The choice will also depend on external factors such as the urgency of the demand for heliostats and the technical difficulties anticipated during commercialization.

2. Production and Installation Process Development

While current glass/metal heliostats have been designed to be compatible with mass production at high levels, efficient mass production processes for building the heliostats have not yet been developed. Since heliostat performance and cost depend on the production processes employed, a successful period of process development is essential before the transition to mass production can occur.

Several aspects of the heliostat design were identified by the suppliers as requiring further process development. The most frequently mentioned area was mirror module manufacturing. Previous mirror module designs have employed complex support, bonding and sealing processes to insure a thirty year life. Conceptual studies of production facilities for these mirror modules (e.g. [4]) have identified areas for potential improvement. Current second generation design efforts will partially alleviate this problem with improved mirror module designs although mass production processes will not be developed and tested.

Other process development needs mentioned by the suppliers include fabrication of heliostat drives and development of field installation equipment.

Production process development usually occurs as a natural result of either preparation for production or the learning that has accumulated during earlier stages of production. In some cases, process development depends on the particular heliostat design and hence applies only to a specific manufacturer. The most effective mechanism for government support for these situations is not by directly funding the manufacturers for process development but instead by encouraging a market for early production and allowing manufacturers to solve production problems internally. Implications for the size of market required to accomplish this will be discussed later. Government funding must still be considered, however, to support research and early development of processes common to all suppliers or of high risk processes that depart radically from earlier production concepts.

3. Design Evolution Resulting from Production Experience

Current heliostats have been developed through several generations of government-funded R&D contracts. The resulting designs for glass/metal heliostats are approaching maturity. This maturity is accompanied by smaller improvements in cost/performance measures (e.g. weight per unit reflective area) with each successive R&D generation. Suppliers believe that further improvements will occur but that production experience rather than continued prototype development is the next logical step. The insights resulting from manufacturing, installing and operating a production quantity of heliostats will be fed back to improve heliostat design. Most suppliers believe that reductions of 15-25% in cost due to design changes will occur as a result of early production experience.

This conclusion does not mean that heliostat research and development should be terminated. New concepts that have the potential for significantly lower costs or improved performance over current glass/metal designs should be investigated.

IV. A Recommended Commercialization Path

The end results of a successful commercialization program as discussed above include design iteration, process development and increased investment in production facilities to satisfy an increasing demand for heliostats. One path for achieving these goals has been formulated. Its major requirements are:

1) Phased increase in heliostat production level
2) Continuity in demand during development and early production
3) Maintenance of competition during early production

The plan outlined here provides for an efficient development of the heliostat industry while simultaneously providing heliostats for demonstrating the central receiver technology to potential users (for a discussion of the interaction of heliostat commercialization with the technology demonstration program see [2]). A more rapid heliostat commercialization path involving greater cost and risk will be discussed in a later section. Specific program recommendations for the nominal commercialization plan are discussed below.

1. Phased Increase in Production Level

Previous production studies as summarized in Appendix B suggest that mass production will dramatically reduce heliostat costs. One difficulty in attaining high production rates is the current low level of heliostat demand that discourages supplier investment in production plant and equipment. However, even if a demand were created instantaneously, sufficient design iteration and processing experience have not been acquired by suppliers to permit an immediate, confident transition into proven mass production processes ($\approx$100K/year or higher). The risks and inefficiencies of a rapid transition would be significantly reduced by periods of production at lower rates. The two production phases that precede mature mass production will be termed intermediate production and initial mass production.

Intermediate production serves an important role in heliostat commercialization. During this period suppliers develop the design and processing experience that will be needed in later mass production. Choice of the production rate must balance the need to keep the production rates low for flexibility and minimal capital investment with the need to increase the production rate in order to develop mass production processes and exploit economies of scale for cost reduction. If the production level is too low, many heliostat components will be contracted out by the suppliers to smaller job shops. As a result, only basic assembly tooling and processes are developed and less relevant production experience is gained by the supplier. If the production level is too high, the large fixed capital investment requires that the heliostat and production process designs be relatively stable since changes will be expensive to incorporate. This will tend to retard implementation of heliostat design or process changes that occur as a result of production experience. Components (such as the mirror module) for which efficient, high volume manufacturing processes are not yet proven would be particularly difficult to manufacture without low level production experience. Most suppliers believe that a production level of 2-5 K annually best balances the above factors.

The duration of this intermediate production is also a factor in commercialization. Production should be continuous for 2-3 years to permit installation and performance feedback to affect design and processing decisions. Cost of these intermediate production heliostats are expected to be somewhat lower than the cost of Barstow pilot plant heliostats because of recent design improvements and an extended amortization period for nonrecurring costs.

Suppliers anticipate that initial mass production at rates of 15-30K annually per supplier can begin following intermediate production. The process development and design iteration activities that will have occurred during intermediate production will provide a basis for scaling production to these higher levels. Heliostat costs will decline due to improvements from intermediate production and to the economies of scale resulting from the higher production rate and longer writeoff period (5-6 years).

Mature mass production involving larger integrated factories could begin after several years of initial mass production experience. Whether such factories become a reality depends on the market success of the solar central receiver concept in the late 1980's.

An exemplary commercialization path is shown in Figure 2. Intermediate production satisfies needs for design iteration and process development. The effect of economies of scale in heliostat production is significant in initial mass production and becomes very important during mature mass production. If demand is sufficient to maintain production levels prescribed by the exemplary path, heliostat manufacturers should be able to solve manufacturing and process development problems during the course of production.

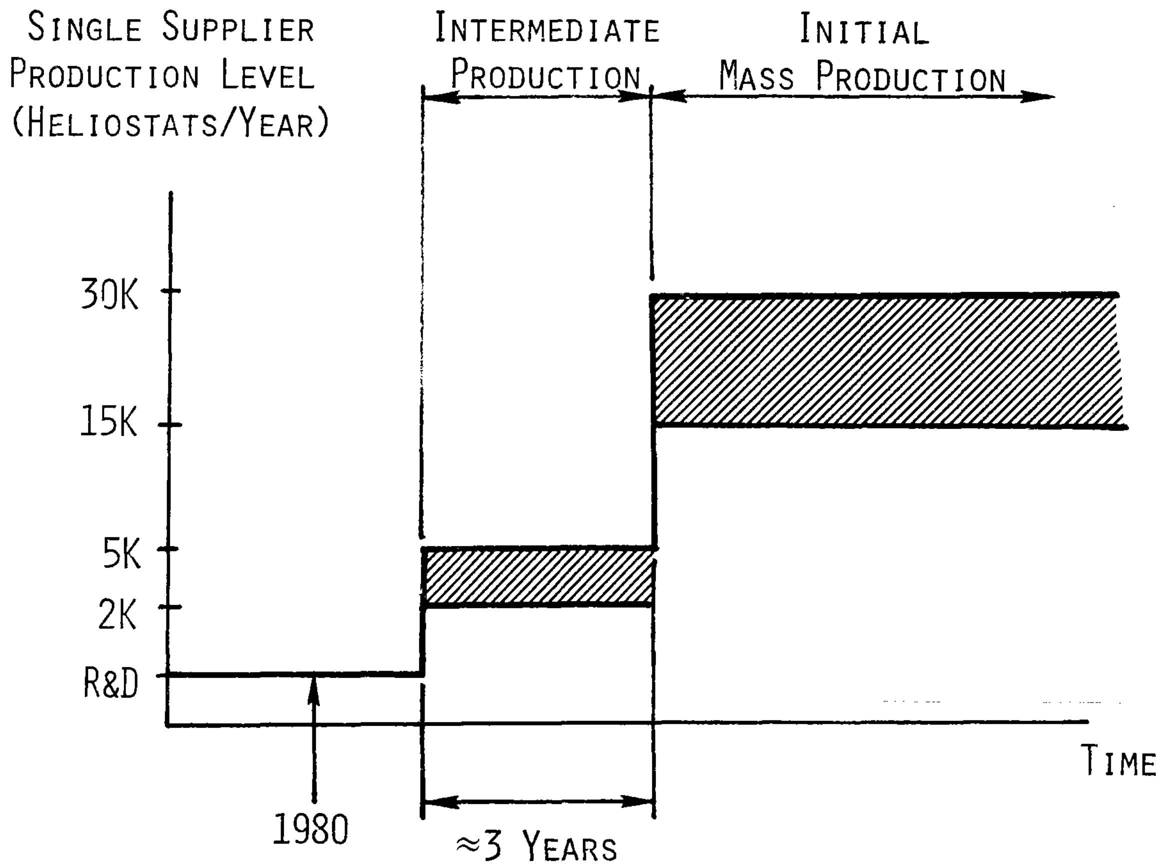

Figure 2. Exemplary Commercialization Path

2. Program Continuity

Successive generations of development contracts have created a nucleus of individuals in various organizations throughout the country who have experience in heliostat design and fabrication. A key concern during the current period of uncertainty regarding future heliostat research, development and production is the maintenance of the expertise acquired to date. Because government programs now provide the major support for heliostat suppliers, government decisions will largely determine heliostat program continuity over the next several years. Absence of continuity would result in loss of a significant investment in research and development. If government programs do not maintain supplier expertise, regaining current capabilities could require larger government expenditures or a better developed market to motivate supplier investments.

3. Maintenance of Competition

The current heliostat development program has benefited from competition among design teams. Maintenance of this competition through intermediate production is necessary to hasten cost reduction and encourage a market for heliostats. If several suppliers have production capability, the availability of heliostats for demonstration programs is more certain and the heliostats will be priced more competitively. The existence of multiple suppliers will also promote private marketing efforts and information dissemination to potential users of the central receiver technology. Many in the heliostat development program feel that maintenance of competition is the single most important need of the intermediate production period.

V. Program Cost

A detailed, independent projection of heliostat production costs was not the focus of the commercialization discussions. Such a projection, to be done properly, would require planning and costing of the production facilities and production inputs needed at each phase of the commercialization process. This was beyond the scope of the study. However, a large body of information is available concerning heliostat costs. This information includes numerous production cost studies as well as historical data on CRTF heliostat costs and pilot plant heliostat estimates. These sources were combined to yield the best available estimate of heliostat cost evolution during commercialization. Note that these estimates are intended to identify the approximate heliostat cost for the commercialization plan [2]. More detailed planning may be needed for heliostat program management.

Intermediate production heliostat costs were projected from currently available estimates for Barstow pilot plant heliostats (Appendix B). Some reduction from Barstow costs should occur due to improvements in design and larger production quantities for amortization of nonrecurring production costs. However, costs will still be well above long term projections for a variety of reasons including low production rates, limited production duration, large first-time demonstration costs and the costs of government participation in contract management.

Initial mass production cost projections were derived from an estimate of the effects of economies of scale and production duration on heliostat cost (Appendix B). Because of the relatively low mass production rate and short production period, initial mass production costs are expected to be approximately 50% higher than projected long term costs.

The projection of heliostat costs during the commercialization period is shown in Figure 3. The total production along the abscissa is based on two suppliers following the exemplary commercialization path of Figure 2. Each supplier produces 2K heliostats per year for a period of three years (intermediate production) followed by 15K heliostats per year for five years (initial mass production). The detailed assumptions used to construct Figure 3 are discussed in Appendix B.

Changes in heliostat cost as a function of time are shown in Figure 4. Program timing is based on an assumed startup date of 1983 for intermediate production. Design and construction of the initial mass production facility begins in 1985 and first production from the facility occurs in 1987. First production from the mature mass production facility is assumed to occur in 1992. Figure 4 illustrates that heliostat costs are predicted to decline significantly during the commercialization period. However, unless an accelerated program is adopted, low cost (<$100/m^2) heliostats will not become available until the early 1990's. Some implications of an accelerated program are discussed in Section VII below.

VI. Implications for Near Term Government Programs

Since there is presently no commercial market for heliostats, the only significant near term demands will be those resulting from government demonstration or incentive programs. Hence it is desirable to structure government participation in such a way that heliostat commercialization can proceed efficiently.

The following list outlines the characteristics government programs should possess to maximize commercialization benefit. They are drawn from the points presented earlier. The most probable application for early production

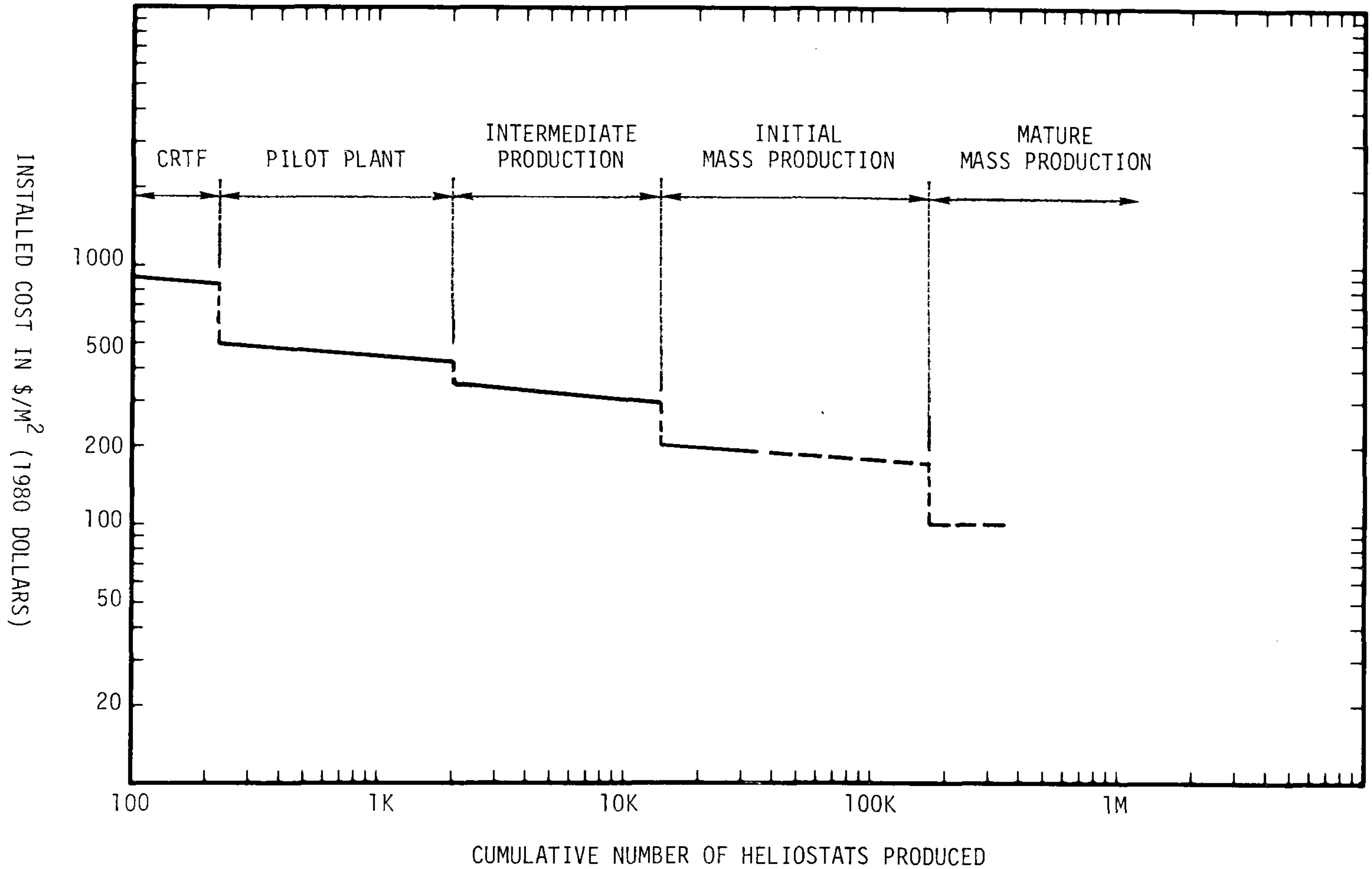

Figure 3. Heliostat Cost Changes During Commercialization

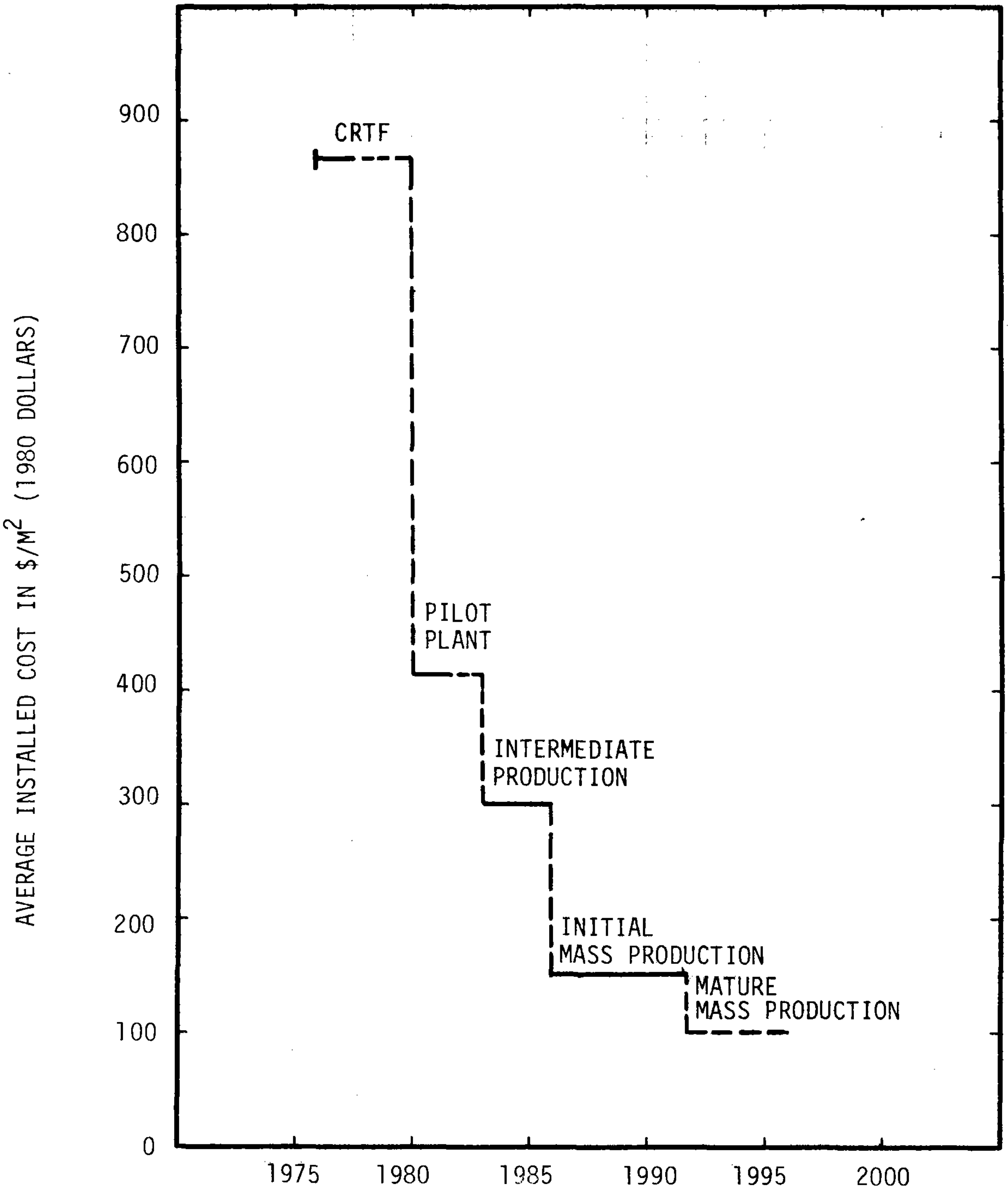

Figure 4. Evolution of Heliostat Costs Over Time

is the repowering/retrofit program [8]. Fulfilling these requirements will advance the heliostat industry at the same time that central receiver technology is demonstrated to potential users.

1. Maintain Competition

Competition (at least 2 or 3 suppliers) should be maintained through intermediate production. Competing designs and production capabilities will accelerate cost reduction and encourage private market development efforts. The addition of new suppliers during the repowering/retrofit program will also bring into production new heliostat designs with potentially greater long run cost effectiveness than earlier production heliostats. The long run competitiveness of the central receiver technology will be enhanced if production of the best available heliostat designs begins as soon as possible.

Competition may occur without government intervention if multiple repowering/retrofit projects are supported and if each site owner is permitted free choice of a heliostat supplier. However, the government must be willing to assume the increased near term costs resulting from multiple production facilities and encourage site owners to diversify their purchases among acceptable heliostat candidates.

2. Produce at Intermediate Production Levels

A production rate capability of at least 2K heliostats per year should be developed by each competing supplier. Production rates below this are useful for maintaining the participation of multiple design teams, but only at production rates approaching 2K/year will significant process development and preparation for later mass production occur.

3. Identify the Costs of Heliostat Commercialization

In near term demonstration programs it is important to differentiate between expenditures for heliostat commercialization (particularly nonrecurring and process development costs) and the marginal (recurring) costs of heliostat production. This will permit an unbiased economic evaluation of the demonstration projects since there will be a clear separation of the cost burden of heliostat commercialization.

VII. An Accelerated Program

The period of intermediate production could be reduced in duration or eliminated entirely if a commitment were made to accelerate the development of central receiver technology. This would result in larger risks due to lack of an intermediate production learning period. The risks inherent in this approach are:

1. Heliostat design will be more difficult to iterate due to large capital expenditures in production tooling.
2. Mass production facility design and startup costs will be increased due to lack of process development during intermediate production.
3. Recovery of large front end costs will have to be guaranteed suppliers through an accelerated demonstration and incentives program.

Because of these risks there is some economic penalty for accelerating the commercialization process. Quantitative estimates of the financial risks in an accelerated program have not been made.

The benefit of early mass production of heliostats is early reduction of heliostat costs. This will cause the technology to become more attractive to users and hence will accelerate private investment in central receiver projects.

The high cost and technical difficulty of a rapid escalation in production rates seem presently to outweigh the benefits of more rapid energy displacement by central receivers. However, this situation could change rapidly due to factors outside of the central receiver program.

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APPENDIX A--ORIENTATION QUESTIONS FOR SUPPLIER MEETINGS

DOE Solar Central Receiver Program Review
Heliostat Commercialization Issues

Recent projections using a reasonable set of economic assumptions have predicted that the solar central receiver concept will be a competitive alternative for the generation of electrical power during the 1990s. Sandia Labs, Livermore, is currently reviewing the central receiver program to determine a commercialization path that will demonstrate system performance and develop component supplier capabilities during this decade. Heliostat commercialization is receiving particular attention because heliostats comprise a large fraction of total plant cost and because heliostat cost reduction depends in large part on development of a mass production capability.

Before commercialization is complete, several hurdles must be cleared. A market for heliostats must exist. But in addition to market factors, technical uncertainties must be resolved, production processes must be developed, and significant investments in production facilities must be made. The attached questions are intended to elicit your views as a potential heliostat supplier concerning the best program for accomplishing these ends.

Heliostat Design Uncertainties

What do you see as the major design uncertainties in current heliostat designs? Are any technological advances required before large scale production of heliostats can begin?

Development of Production Capability

How can a capability for large scale production of heliostats be most efficiently developed? Will continuing generations of R&D contracts be sufficient? Is low level production required for a period of time? Or should the government make a large purchase to induce suppliers to invest in mass production facilities as soon as possible?

What are the specific design and process development problems that must be solved before heliostats can be mass produced? How do the solutions of these problems depend on the size and stability of heliostat orders during the next five years?

Recommended Government Actions

Since no significant private market for heliostats is expected to exist in the near term, government policy will determine the demand for heliostats. What level of government-induced demand will expedite early solution of process development problems?

Current plans for solar central receiver development require several thousand heliostats for a variety of demonstration projects (e.g. repowering) during the 1980s. How should these orders be structured to promote solution of design and manufacturing problems? Will the cost of repowering and subsequent heliostats depend on the characteristics of early orders? What particular advances would you like to see made during this early production?

The R&D program has attempted to maintain competition among a number of potential heliostat suppliers. Should efforts be made to maintain this competition through early stages of production? How would you expect competition to affect design evolution and costs?

Heliostat Costs and Price

How would you expect heliostat costs to change over time if the best commercialization program were adopted? What are the factors accounting for cost changes (e.g. design changes, more efficient processing, economies of scale, etc.) and what is the relative importance of each? How large are front end costs (including capital and process development costs) at each stage of production development?

Current projections of the heliostat market are very uncertain. Under these conditions, how would you evaluate investments in a production facility? How fast would you expect to recover process development and capital costs?

APPENDIX B--A SUMMARY OF HELIOSTAT COST DATA AND ASSUMPTIONS

Over the course of heliostat development, there have been many engineering cost estimates predicting the production costs of heliostats. Some data also exist from CRTF heliostat purchases and pilot plant heliostat costs.

This appendix summarizes a range of these sources and extrapolates the information to derive Figures 3 and 4 in the text. The first half of the appendix projects a cost for intermediate production heliostats based on the estimated costs of pilot plant heliostats. The second half of the appendix summarizes several production cost estimates and uses them to project mass production costs.

1. Heliostat Costs During Intermediate Production

Cost estimates for intermediate production heliostats are based on the Martin Marietta cost proposal for Barstow pilot plant heliostats and on the government contracts for foundations, wiring and glass [9, 10]. The pertinent data concerning proposed Barstow costs are listed below.

	Factory Cost in $\$/m^2$	
Martin Marietta Data (1818 heliostats)	Average	Variable (Recurring)
Proposal Price (1981 dollars assumed)	386	250
Deflated to 1980 dollars	350	225

The variable (recurring) price was estimated from option prices for increasing the number of heliostats produced [9]. The variable price approximates the price of an extra unit produced after initial lot production is complete assuming all fixed production costs have been charged to previously produced heliostats.

Costs of government-furnished material at Barstow are tabulated below [10].

	1980 dollars in millions	
Foundations	$1.24	
Wiring	1.83	
Glass	.86	
Software (est.)	.10	
	$4.03	≈ $55/m^2

The sum of the above factory cost and government-furnished material yields an estimate of the overall installed cost of the Barstow heliostats.

The assumptions made to project intermediate production prices from these data are listed below.

Assumption

1. Each supplier will produce 5000 heliostats (50 m^2 each).
2. Barstow foundation, wiring, glass and software costs are assumed.
3. Design changes will reduce factory costs by 15%.
4. Single supplier nonrecurring cost will be 8 million.
5. Factory costs decline along a 95% labor learning curve.

These assumptions are not based on a detailed estimate of intermediate production designs and production facilities. However, they yield a good approximation of heliostat commercialization costs. More detailed estimates may be required for program management purposes.

By assumption 3, the variable cost of the 1818th unit in intermediate production is

$$C_{V\ 1818} = \frac{225}{1.15} = \$196\ /m^2$$

The analytical form of the labor learning curve is given by

$$\ln C = K_1 \ln Q + K_2$$

where C = unit cost

Q = quantity produced in production facility

K_1, K_2 = constants

In this case the learning curve is fitted to the variable cost of the 1818th unit. Let (C_{V0}, Q_0) = (\$196., 1818) then the average variable cost for a total production run of Q_T is given by

$$C_{VT} = \frac{C_{V0}}{Q_0^{K_1}} \frac{1}{(K_1 + 1)} Q_T^{K_1}$$

This is simply the area under the cost curve divided by the total production. For the intermediate production case

Q_T = total production = 5000

$K_1 = \frac{\ln .95}{\ln 2}$ for a 95% labor learning curve

These parameters yield an average variable cost of

$C_{VT} = \$196.\ /m^2$

Coincidentally, the average variable cost for the 5000 unit run is approximately equal to the variable cost of the 1818th unit. The overall cost is the sum of the variable production cost, the fixed (nonrecurring) production cost and an allowance for foundations, wiring, glass and software. The average fixed production cost C_{FT} is a rough allocation that does not model return on investment and tax effects.

$$C_{FT} = \frac{(\$8. \times 10^6)}{(5000)(50m^2)} \approx \$32.\ /m^2$$

The overall installed cost is given by

$C_T = 196 + 55 + 32 = \$283/m^2$

For simplicity this is rounded to \$300/m² for commercialization estimates.

2) Heliostat Costs During Mass Production

Commercialization cost projections for the mass production phases have been drawn from the large collection of existing heliostat production cost studies. A recent group of studies has examined production of the MDAC Prototype design. Cost data from these studies are summarized in Table B-1.

There are significant differences among the cost studies. Some of the differences result from differing ground rules. For example, the GM study used current quotations on purchased components while the MDAC and Battelle studies used quotations based on stable future orders to a component supplier following several years of component development. Other differences are based on the level of capital investment chosen for the production facility. Large capital investments are more expensive initially but reduce heliostat recurring costs. Insufficient experience exists currently to determine the optimal balance of capital and labor in production.

The data of Table B-1 can be used to quantify the effects of economies of scale and production duration on heliostat cost. If mature mass production at a rate of approximately 250K heliostats per year is assigned a relative cost of 1.0, the ratio of production costs for lower volumes to mature mass production costs identifies the economies of scale. This has been done for each of the independent sets of MDAC Prototype estimates shown in Table B-1. The results are plotted in Figure B-1 as a function of the total production from a production facility during its expected lifetime. For example, if a 2K heliostat/year facility operates for 5 years, the total lifetime production from the facility is 10K units. Lifetime production rather than production rate is used in Figure B-1 as an indicator of the total future market needed to stimulate investment in the heliostat production facilities required to reduce costs. The high relative cost for small production quantities reflects both the low production rate and the relatively short production lifetime needed to satisfy the demand. The large total production quantities associated with mature mass production indicates that suppliers will not invest in high volume production facilities until a stable, long term market is anticipated.

The economies of scale relationships in Figure B-1 were derived by assuming a particular heliostat design--the McDonnell Douglas Prototype design. Later generations of the glass/metal heliostat will have different designs and hence different absolute costs at each production level. As the design evolves, the cost at high production levels is expected to decline. However, the variation of cost with production quantity will be approximately as shown in Figure B-1 unless a radically new design concept emerges. Design differences can cause some shifts of the relative cost curve particularly at very low production levels. However, the shifts are not expected to eliminate the significant reduction in cost associated with increased production. Total production quantities used to plot Figure B-1 are derived by assuming production would occur for three years at 2.5K/year and five years at the higher rates of 25K/year and 250K/year.

The results shown in Figure B-1 and Table B-1 were used to project heliostat costs for the initial and mature mass production phases of commercialization. Based on all of the studies summarized in Table B-1, mature mass production of the MDAC Prototype design will result in installed costs of less than $\$100/m^2$. Initial mass production cost estimates were obtained by multiplying the mature mass production estimate by the appropriate economies of scale factor (based on 5 years production at 15 K/year) from Figure B-1. The resulting estimate is approximately $\$150/m^2$. These projections are summarized in Table B-2

TABLE B-1
HELIOSTAT COST DATA SUMMARY

SOURCE	DESIGN	PRODUCTION RATE (Number/Year)	PRODUCTION FACILITY CAPITAL COST (Millions of $)	INSTALLED COST ($/m^2)
CRTF	CRTF	222 (Single Lot)	--------	860
Pilot Plant	Pilot Plant	1818 (Single Lot)	4[a] (Nonrecurring)	420
MDAC	MDAC Prototype	2.5 K	8[b]	200[b]
		25 K	10-15	79
		250 K	-----	67
GM	MDAC Prototype	25 K	91	130
		250 K	412	93
Battelle	MDAC Prototype	2.5 K	9	220
		25 K	34	96
		250 K	169	85

[a] Author's Estimate
[b] Author's Extrapolation of MDAC single lot estimates to 3 years continuous production.

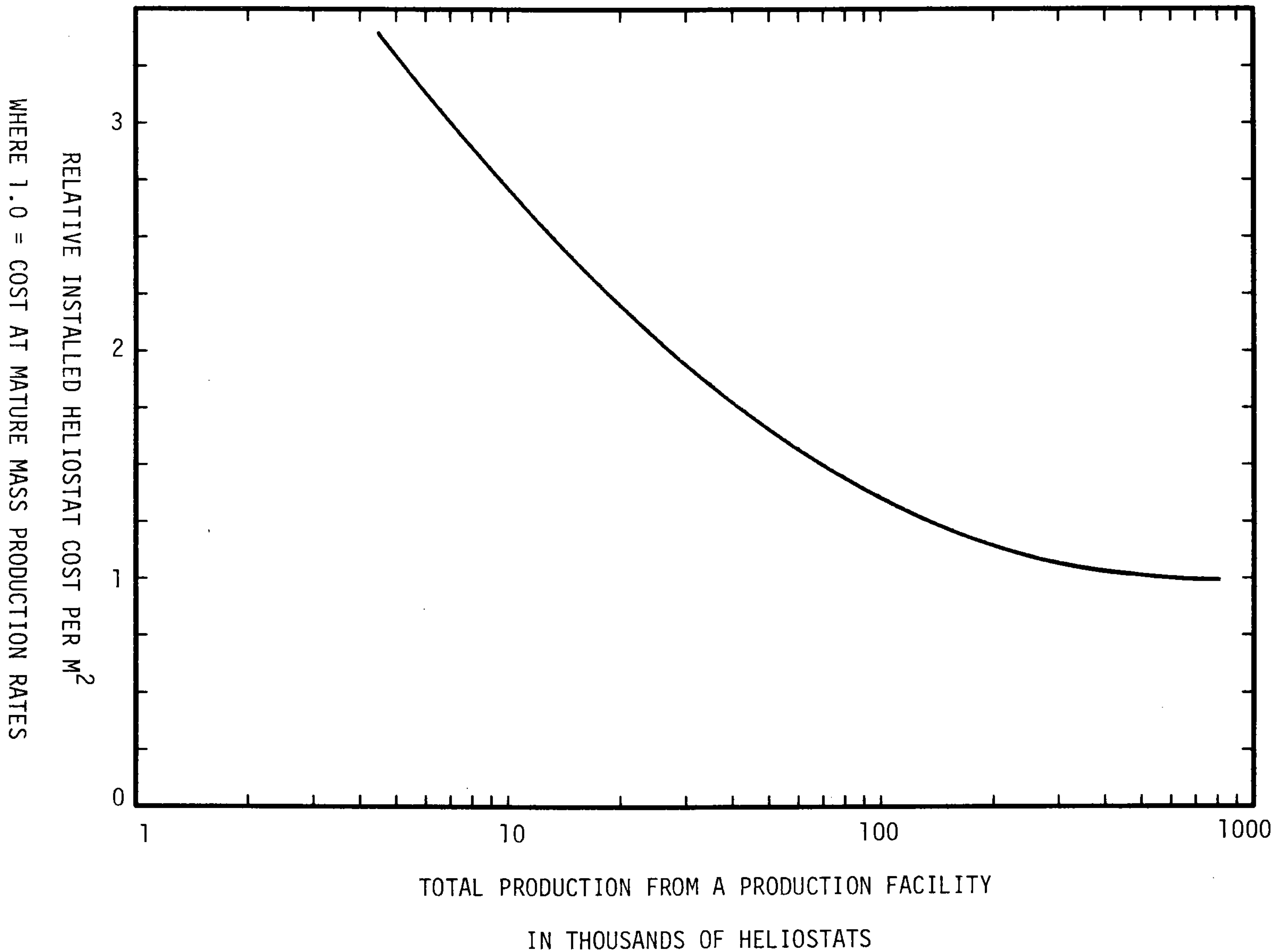

Figure B-1. Economies of Scale in Heliostat Production (MDAC Prototype Design) and are graphed in Figures 3 and 4. In Figure 3 a small degree of labor learning (95% learning curve) is plotted as a cost reduction mechanism.

TABLE B-2
HELIOSTAT COST PROJECTIONS FOR COMMERCIALIZATION

Commercialization Phase	Annual Production Per Supplier (per year)	Minimum Total Production (2 Suppliers)	Approximate Average Cost (1980 $/m^2)
Intermediate Production (3 years)	2-5 K	12 K	300.
Initial Mass Production (5 years)	15-30 K	150 K	150.
Mature Mass production	≈100 K and above	-----	< 100.

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