SOLAR CENTRAL RECEIVER TECHNOLOGY AND APPLICATIONS

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ABSTRACT

The 10 MWe solar pilot plant at Barstow, California, will shortly provide some thousands of homeowners with electricity from the sun. The plant consists of 1818 heliostats that reflect the solar radiation to a boiler atop a 76 meter high tower near the center of the configuration. Each heliostat has an area of 40 m^2. Turbine inlet temperature is 950^{0}F at a pressure of 1450 PSI. The output of this plant is being connected to the Southern California Edison electric grid with a capacity sufficient to supply the electrical needs of 7,000 individuals. Plant construction of the joint DOE-utility project is complete and turbine roll is expected shortly. Further applications of this concept is under consideration, involving the range 10-300 MWe intermediate and quasi-baseload utility units. This present report summarizes projected capital costs, busbar energy costs vs. capacity factors, financing alternatives and economic viability. Advantages of the central receiver concept once implemented include substantial oil and gas savings, stabilizing

effect on energy costs, short energy payback period of 18 months in terms of electrical energy, short construction period, generation of substantial tax revenues vs. governmental investment, utilization of a wide labor spectrum, and minimal environmental effects.

INTRODUCTION

The solar central receiver concept is a design to collect energy from a large flat land area by reflecting solar beam energy from a large number of mirrors or heliostats onto a single large receiver or boiler atop a tall tower near the center of the heliostat field. The heliostat field and the boiler that is located at focal point simulate a large parabola; the parabola axis is fixed vertically and the mirror segments are continuously reoriented to steer the beam energy onto the receiver.[1-3] This system can achieve quite high concentration ratios and consequent boiler temperatures, the latter being sufficient to supply high quality steam to conventional turbo-electric generators used by electric utilities. Water is pumped up the tower and is converted to steam which drives the turbine at the base of the tower. Turbine inlet temperature is $950^{o}F$ at 1450 PSI.

The 10 MWe (10,000 KWe) plant constructed at Barstow, California,[4] is shown in Figure 1. The field of heliostats numbers 1818 with each having a mirror surface area of 40 mm^2 and a total mirror area of about 70,000 m^2. The land area enclosed by the heliostat field is about 75 acres. Figure 2 is a system drawing showing the relationships between the heliostat, receiver, and storage facilities. This plant can supply the electrical needs of some 7,000 individuals and is being connected into the Southern California Edison plant grid. The plant capacity factor is 35 percent. The builders and operators are Southern California Edison, Los Angeles Water & Power and the California Energy Commission. The prime system design and integration contractor is McDonnell Douglas Astronautics. The heliostats are supplied by Martin Marietta Corporation, the boiler and storage by Rockwell International. The Architect and Engineer is Stearns & Rogers and a University of Houston team is the designer of the heliostat field layout. Plant construction of the DOE-Industry project is complete and turbine roll is expected shortly.

This first-of-a-kind pilot plant costs $140M with $21.5M funded by the plant builders and the balance by DOE. The heliostat costs are expected to be lowered considerably in the future through mass production and it should be recognized that the cost per kilowatt electric for smaller plants, regardless of energy source is higher.

This first of a kind plant was not optimized for 10 MWe operation but was scaled to gain experience with 100 MWe sizes which are of much greater interest to utilities. These type plants can be constructed in the range of 10-300 MWe size, with an optimum occurring toward the larger sizes, and can be operated with storage such that capacity factors of 0.6-0.8 are obtained (use of an air-rock storage system could provide quasi-baseload power). The most significant factor needed for price reduction is mass heliostat production. A series of studies have been performed to estimate as accurately as possible heliostat costs as a function of production rate. Figure 3 is a summary of the estimated costs of heliostats versus production.[5] Further details of expected cost reductions are shown in Table 1.[5] These results have been verified by a number of studies including a detailed analysis of a particular heliostat design by a General Motors group.[6] It should be noted that once the central receiver system enters the market that the heliostat costs will have a stabilizing effect on energy costs.

There are a number of advantages that can be realized by the adoption of the solar central receiver as an energy option, and these include the utilization of American labor in construction and operation rather than American dollars used in buying oil. Also significant oil savings can be realized. Each 100 MWe plant with a capacity factor of 0.4 can displace 7.7×10^5 barrels of oil annually. In addition the environmental effects are minimal for these systems. They can be operated with dry cooling as well as with conventional wet cooling towers, and are ideally suited for the desert Southwest where other energy sources such as nuclear and even coal are difficult to introduce. The energy payback of these systems appears to be quite good. Specifically, on an electric basis, only 1.5 years is required to return the capital energy used in creating the plant. The estimated O & M costs for 100 MWe plant appear quite reasonable.

CURRENT ECONOMICS (Busbar Energy Cost - BBEC)

There are a variety of heat transport fluids that can be employed in full-scale solar central receiver power plants. These include water/steam, which is used in the Barstow plant), draw salt, sodium and air. The salt heat transport fluid and the sodium heat transport fluid can be used as the storage medium as well. Air/rock storage has also been proposed in conjunction with sodium-cooled plants. Because of time limitation in the preparation of this paper only the sodium receiver concept will be used to indicate the economic potential of the solar central receiver. Salt-cooled system would have economics comparable with sodium. In Figure 4 is shown a system schematic of a sodium central receiver plant as visualized by Rockwell International Corporation, one of several companies involved in solar plant designs. In Table 2 is a detailed summary of the key characteristics of a 100 MWe and 281 MWe sodium central receiver plant[7]. The capital cost of such plants as a function of capacity factor is given in Table 3.[7]

A comparison of the cost of energy as produced by a variety of conventional energy options and as a function of capacity factor is shown in Figure 5 in relation to the cost of energy from the solar plant.[7] Two heliostat costs are used, one at $\$100/\text{m}^2$ and the other at $\$78/\text{m}^2$. These costs are considered attainable values if mass production is employed. The heliostat costs are given in 1980 dollars. In Figure 6 are shown additional comparisons of the cost of energy from oil-fired plants relative to that for solar for current heliostat costs[7]. The cost of ~~$\$216$~~ $\$175/\text{m}^2$ has recently been quoted for single orders of the order of 17,000. It can be seen from these figures that solar systems can potentially compete with oil and gas fired power plants at moderately high heliostst cost. In general the solar option is most competitive at lower capacity factors typical of intermediate load demand. The reason for including nuclear here is to clearly demonstrate the complementary nature of the solar and nuclear options. Nuclear is the lowest cost system in baseload operation under the assumptions used here, but not all load demand requirements are in the baseload regime. A considerable amount of energy demand is of the intermediate and peaking type which can be supplied in a cost effective manner by solar central receivers. Part of this cost effectiveness is related to the fact that in many areas times of higher load demands for electricity match reasonably well with the hours when the sun is shining. Thus storage time of the order of 3 or 4 hours are frequently optimal. Although additional storage is cost effective in terms of lowering the cost of energy from the solar plant, additional storage may place the solar plant into the baseload range where it may not economically compete with coal or nuclear if the grid mix contains these options. In any case, the solar central receiver, unlike many renewable energy systems, can incorporate large amounts of storage in a cost effective manner and is therefore, very versatile in terms of its application in the utility grid.

One question that frequently arises regarding the economic competitiveness of the solar plant relative to nuclear and coal is the size factor. The most cost effective coal and nuclear plants are usually of large size; i.e., of the order of 600 MWe or greater. Also the problems associated with permits and licensing dictate the installation of large plants. In order to properly compare solar plants with coal or nuclear, therefore, one should use comparably sized units. Figure 7 shows that the capital cost of coal and nuclear plants rises rather steeply as the size approaches that of the optimum solar plant (i.e., 100 to 300 MWe)[8]. Thus the data used in figure 5 are probably conservative insofar as the capital cost assumptions for small-size coal and nuclear plants are concerned. It follows also that the costs associated with the 10 MWe Barstow plant would appear to be more reasonable in view of its size and the fact that it is the first-of-a-kind.

In Figure 8 is a comparison of plant value to a utility for a solar plant with an oil plant.[7] If indeed heliostats can be bought for $175/m^2 in the near term and there is little uncertainty in costs estimates, the solar system is competitive. At any rate the solar central receiver competitiveness is rapidly coming into range with other energy sources.

The question can be raised as to why commercialization has not already occurred without further Government involvement. There are several perceived technical/cost barriers that need to be removed. The heliostats are not in mass production and yet a clearly identified market is needed to stimulate mass production. At the present time all cost estimates for all-liquid type systems are based on conceptual designs. Also no complete, large-s e, all-liquid system has been constructed and operated, and certain key, f l-scale components have not been built and tested. Utilities find it very isky to buy a full-scale system, unless a reasonably large scale demo has b n built and operation been verified, where the components have only operated n small sizes. They would like to see risk reduction so that venture capital ould be more readily brought into play. This can be accomplished, it is bel ved, by testing larger size boiler components and by developing detailed chnical design for at least two plants so that detailed financial discussion ould be undertaken. The detailed design would permit narrowing of the cost stimate of plant value and through several scaled component tests, reduce pe ormance uncertainty. With a detailed design, a utility would have less diff ulty in developing capital, by providing information to Public Utility Commis ons and financial parties that they would not otherwise have available them. Finally, it is believed imperative to provide some form of cost sh ing for the introduction of the first few plants. This could be accomplish either through guaranteed loans or continuance of the Business Investment Ta Credits with the latter being preferred.

MARKET POTENTIAL

A time scale for potential commercialization of this energy res irce is shown in figure 9.[7] We are confident that once several commercial 00 MWe plants are in operation this technology will be used extensively. e most attractive approach would be to repower existing oil or gas fired pl s with the addition of a central receiver system on site to provide heat d fuel savings. A conservative scenario for electric power generation alone tlines planning and construction potential to the year 2000 in figure Once developed, the market is expected to be considerably larger than 0 quads annually and would include process heat delivery. The installed ele ricity capacity expected by 2000 is shown at 13.3 gigawatts with an an al oil savings of 103 million bbls.

SUMMARY

There are a number of benefits that would accrue from utilization of this resource. Once commercialization is attained, the cost to the consumer of electrical power from solar systems will be more stable and potentially lower than that from conventional energy sources. The Southwest is in a unique position to utilize solar plant development where nuclear and coal sitings are difficult. Also the U. S. would benefit in general either by the installation of long DC transmission lines or by the fact that oil and gas not used in one region would be more readily available in another. Cumulative oil savings could exceed 373 million barrels by year 2000 and costs for constructing solar plants invest in the American labor market rather than a foreign country. There are no fuels to transport or handle, no CO_2 emissions, no combustion byproducts, no solid wastes, and a short construction period of 3-4 years.

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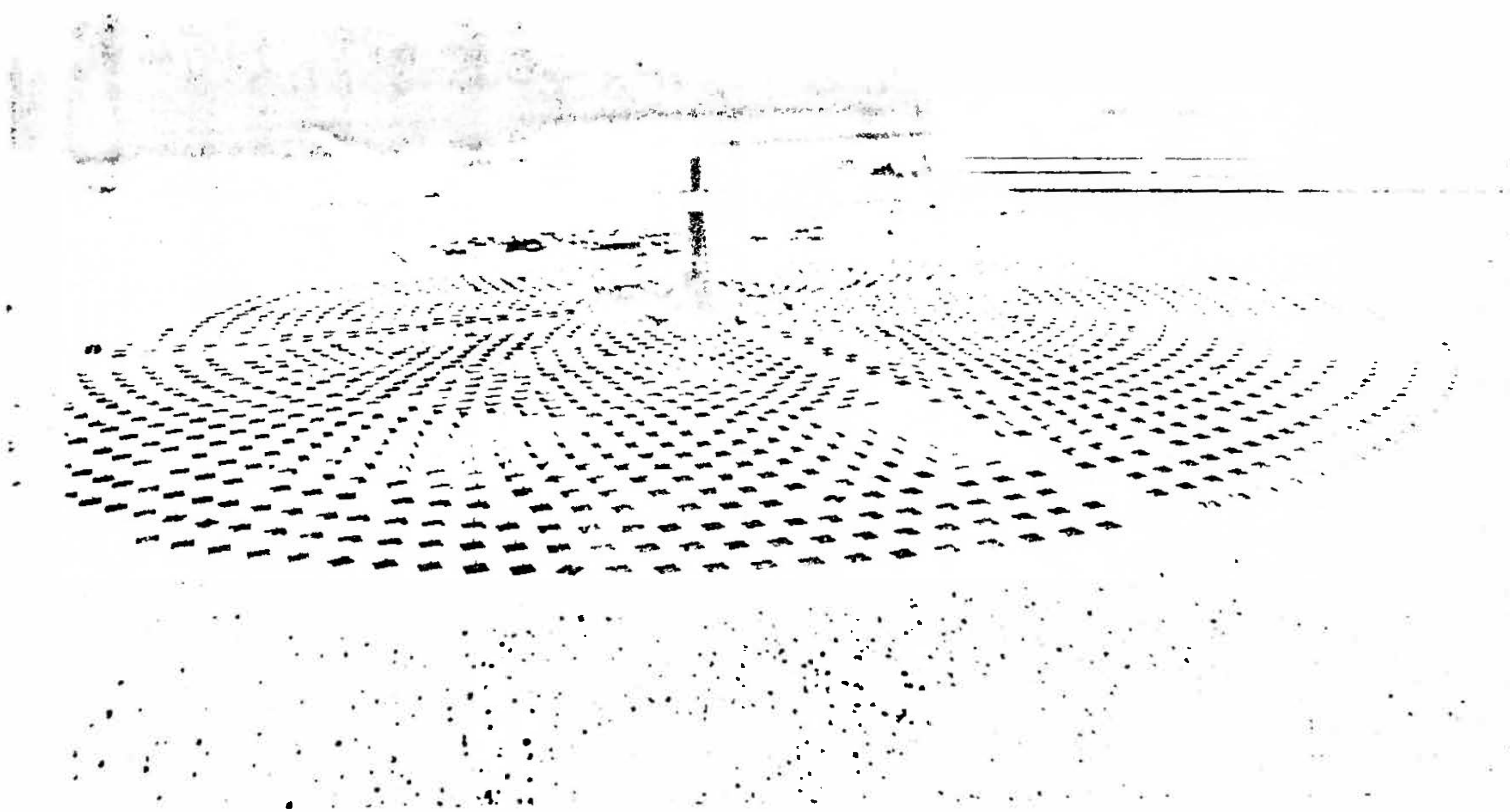


Fig. 1 Barstow 10 MWe Pilot Plant

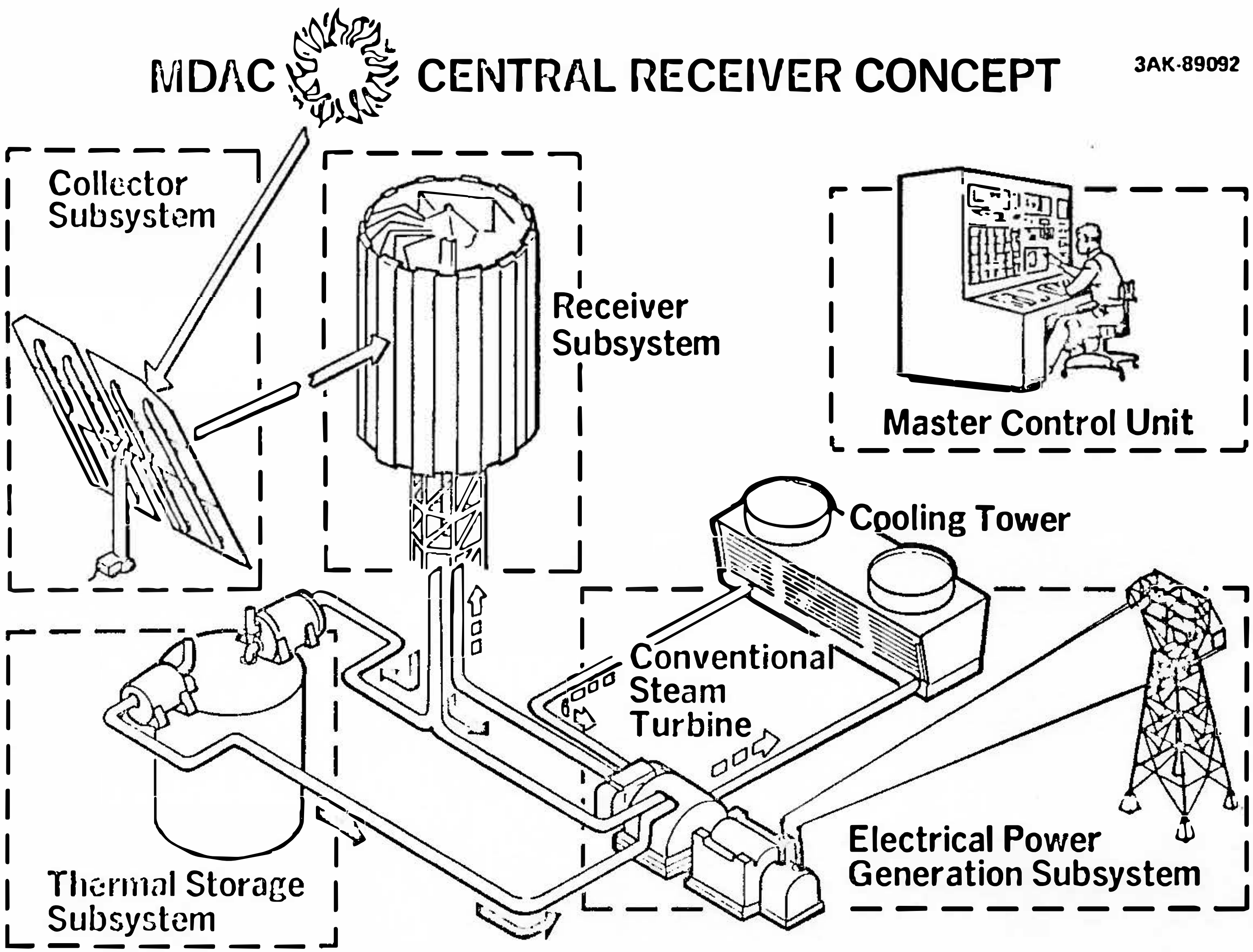

MDAC CENTRAL RECEIVER CONCEPT
3AK-89092
Collector Subsystem
Receiver Subsystem
Master Control Unit
Cooling Tower
Conventional Steam Turbine
Electrical Power Generation Subsystem
Thermal Storage Subsystem

Fig. 2

HELIOSTAT COST CHANGES DURING COMMERCIALIZATION

VBA186

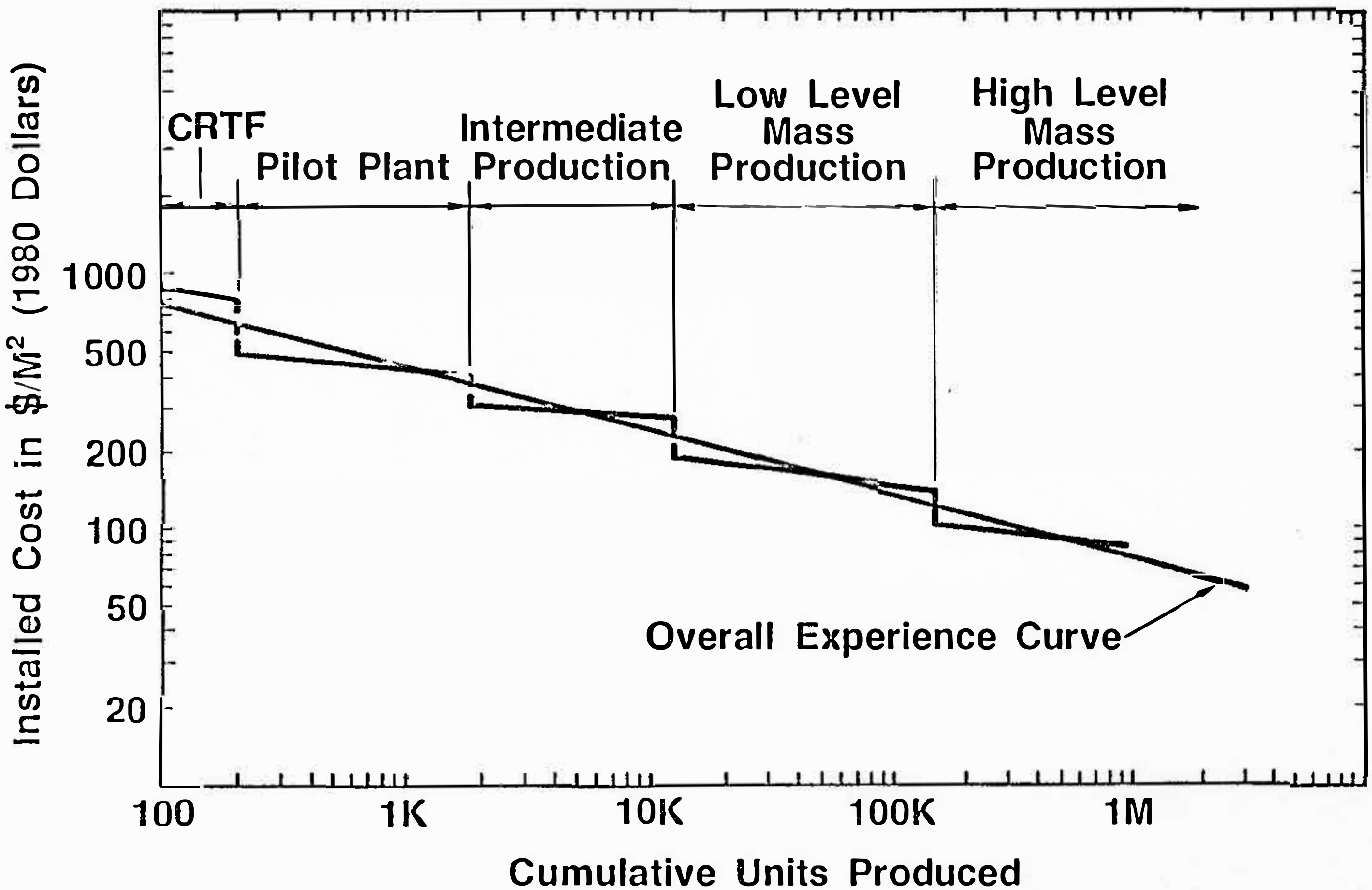


Fig. 3

2ND GENERATION HELIOSTAT ESTIMATED FUTURE REDUCTION IN PRICE ($\$/m^2$)

	Installed Price	Contractor Estimated Reductions	Effect of Learning (10 yrs)	Potential Price 10th yr
ARCO	118	27[1]	12	79
BEC	147	15[2]	15	117
MMC	109	7[3]	11	91
MDAC	111	18[4]	11	82

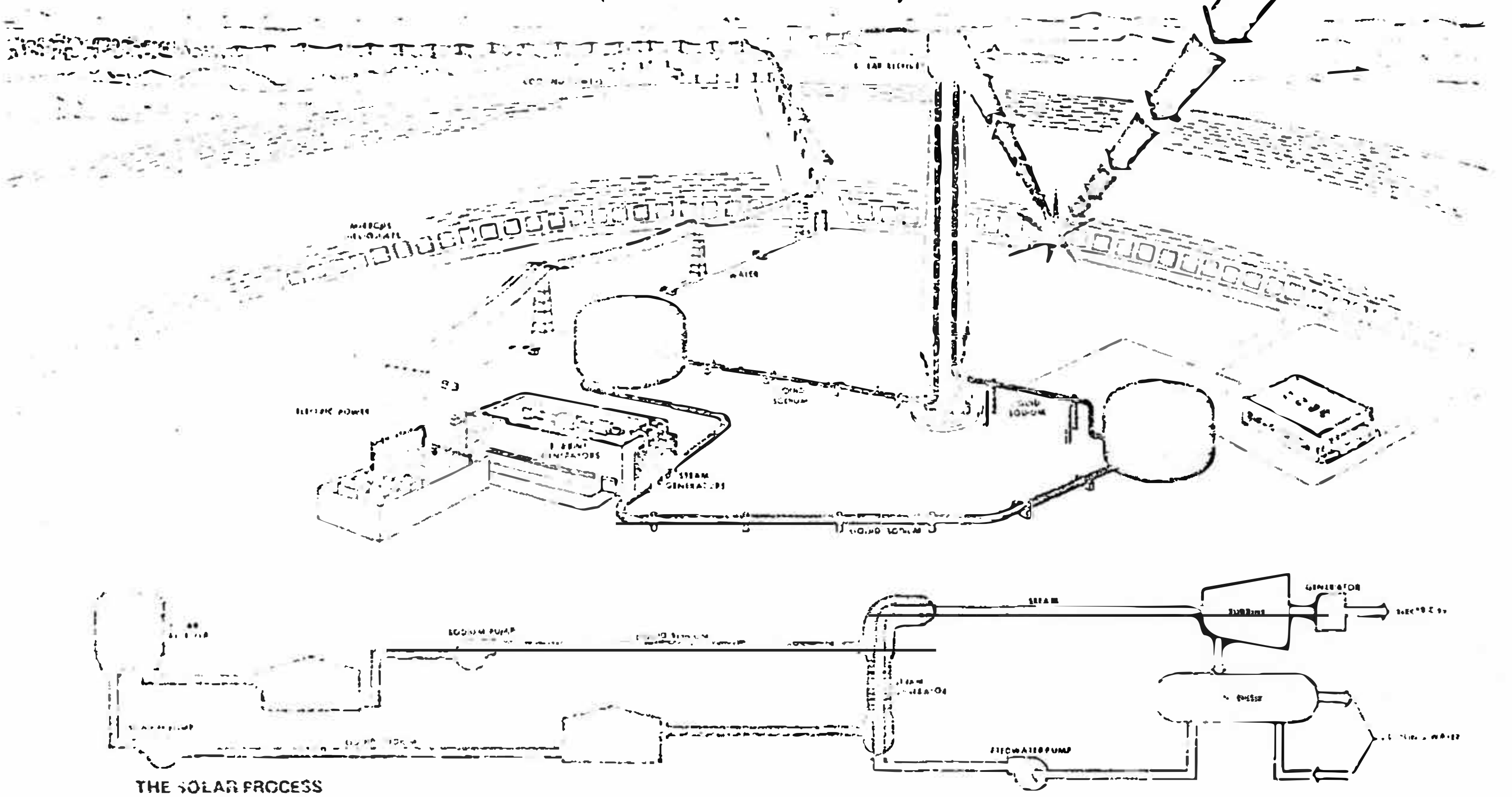
1. Use thin glass, one piece mirror w/o paint; reduce casting weight, redesign motors; redesign a torque tube; replan field assembly labor; use lifetime finishes; refine controls.
2. Reduce pedestal diameter; reduce gimbal diameter; use foamglas in core; reduce silvering cost; reduce drive motor cost.
3. Remove mirror paint; refine foundation/pedestal; refine controls, field wiring installation.
4. Remove shim's, edge seals; add 14% more area; refine foundation; decrease cure times.

Table 1

SOLAR POWER PLANT

SODIUM COOLED CENTRAL RECEIVER

(STAND-ALONE SYSTEM)



THE SOLAR PROCESS

- THE SUN'S RAYS ARE REFLECTED BY THE MIRRORS (HELIOSTATS) ONTO THE SOLAR RECEIVER
- THE RECEIVER ABSORBS THE SUN'S ENERGY IN THE FORM OF HEAT FROM ITS RAYS
- LIQUID SODIUM FLOWING THROUGH THE RECEIVER ABSORBS THE HEAT
- THE HOT LIQUID SODIUM FLOWS FROM THE RECEIVER TO A HOT STORAGE TANK, THEN TO A STEAM GENERATOR (THE HOT TANK ACCUMULATES SUFFICIENT LIQUID SODIUM DURING THE DAY, TO PERMIT UP TO 14 HOURS OF STORAGE FOR NIGHT-TIME OR CLOUDY DAY OPERATION. OPERATION IS AT FULL POWER GENERATION)
- IN THE STEAM GENERATOR, THE HOT SODIUM HEATS WATER TO STEAM. THEN IT FLOWS BACK TO THE RECEIVER THROUGH THE COLD STORAGE TANK TO COMPLETE THE SODIUM CYCLE
- THE STEAM FLOWS TO THE TURBINE WHICH DRIVES AN ELECTRIC GENERATOR

RESULT — ELECTRICITY FOR YOUR HOME AND WORK PLACE

Fig. 4

SODIUM CENTRAL RECEIVER SOLAR PLANT DATA SUMMARY

SYSTEM	PARAMETER	CONFIGURATION: FINAL BASELINE	CONFIGURATION: OPTIMUM BASELINE
ELECTRIC	NET POWER (MWE)	100	281
	GROSS POWER (MWE)	112	312
	CYCLE EFFICIENCY (%)	43.1	43.2
RECEIVER	SOLAR MULTIPLIER (SM)	1.50	1.50
	THERMAL POWER (MWT)		
	NOMINAL	260	723
	MAXIMUM	390	1,084
	RECEIVER TEMPERATURE $^{0}C(^{0}F)$	288(550)	288(550)
	IN	288(550)	288(550)
	OUT	593(1100)	593(1100)
	RECEIVER MIDPOINT ELEVATION M(FT)	174(571)	268(879)
STORAGE (100% POWER)	OPERATING TIME (H)	3	3
	ENERGY (MWT-H)	812.5	2,400
	QUANTITY 10^6KG(10^6LB)	7.6(16.8)	23(50.4)
ELECTRIC POWER GENERATING	TURBINE IN PRESSURE MN/M^2(PSIG)	12.4(1800)	16.5(2400)
	SUPERHEATER TEMPERATURE $^{0}C(^{0}F)$	538(1000)	538(1000)
	REHEATER TEMPERATURE $^{0}C(^{0}F)$	538(1000)	538(1000)
COLLECTOR	MIRROR AREA KM^2(FT^2)	0.692(6.95x10^6)	1.99(21.4x10^6)
	NUMBER OF HELIOSTATS	14,106	40,660
	TOTAL LAND AREA (ACRE)	780	2,220

Table 2

ESC-BD-79-28

PLANT CAPITAL COST ESTIMATES

(NTH PLANT) (1980 $ IN MILLIONS)

SIZE/STORAGE	REPOWERED	STANDALONE	
	100 MWE/3HR	100 MWE/3HR	281 MWE/3HR
COLLECTOR SUBSYSTEM (HELIOSTAT COST = 100 $/M^2)	78	78	229
RECEIVER SUBSYSTEM	24	24	59
THERMAL STORAGE SUBSYSTEM	7	7	18
EPGS & MISCELLANEOUS	9	40	77
	118	149	383
$/KWT* (IN DOLLARS)	305	384	352

*THERMAL ENERGY DELIVERED TO BOTTOM OF TOWER

Table 3

BUSBAR ENERGY COST COMPARISONS

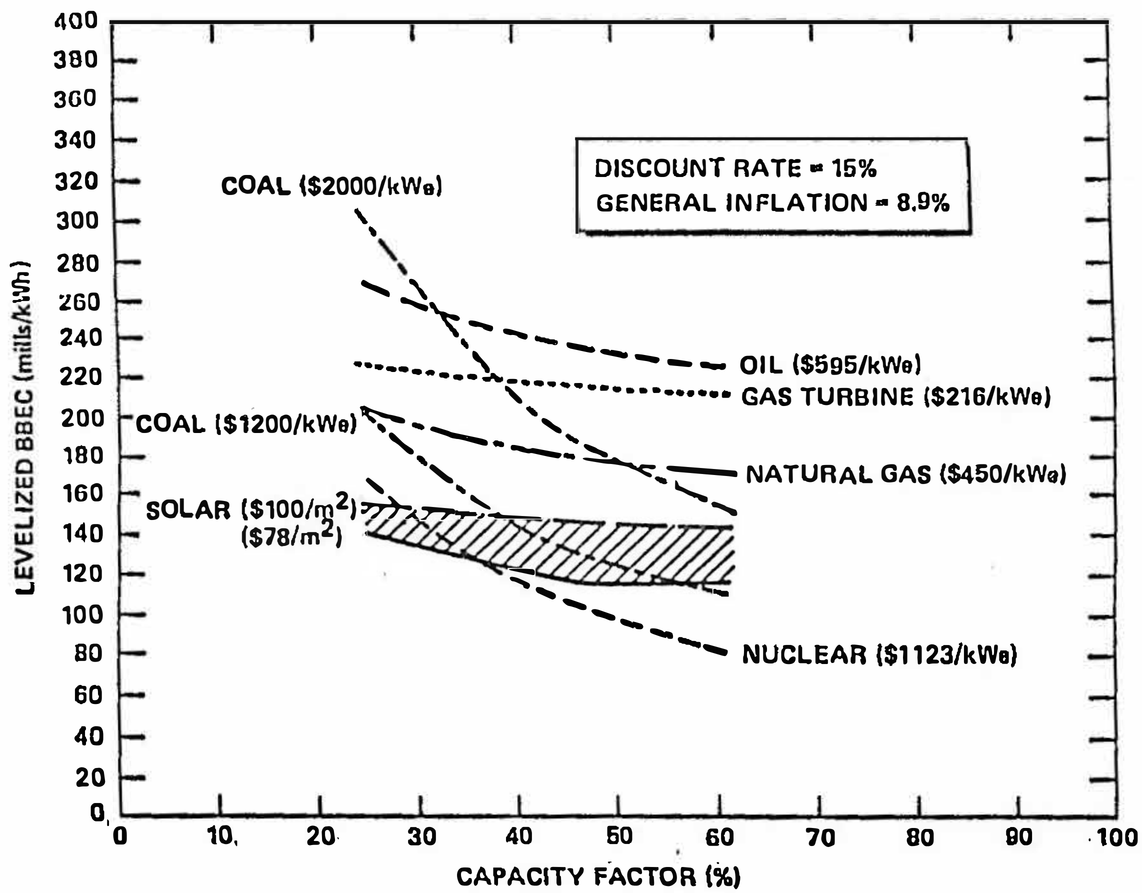


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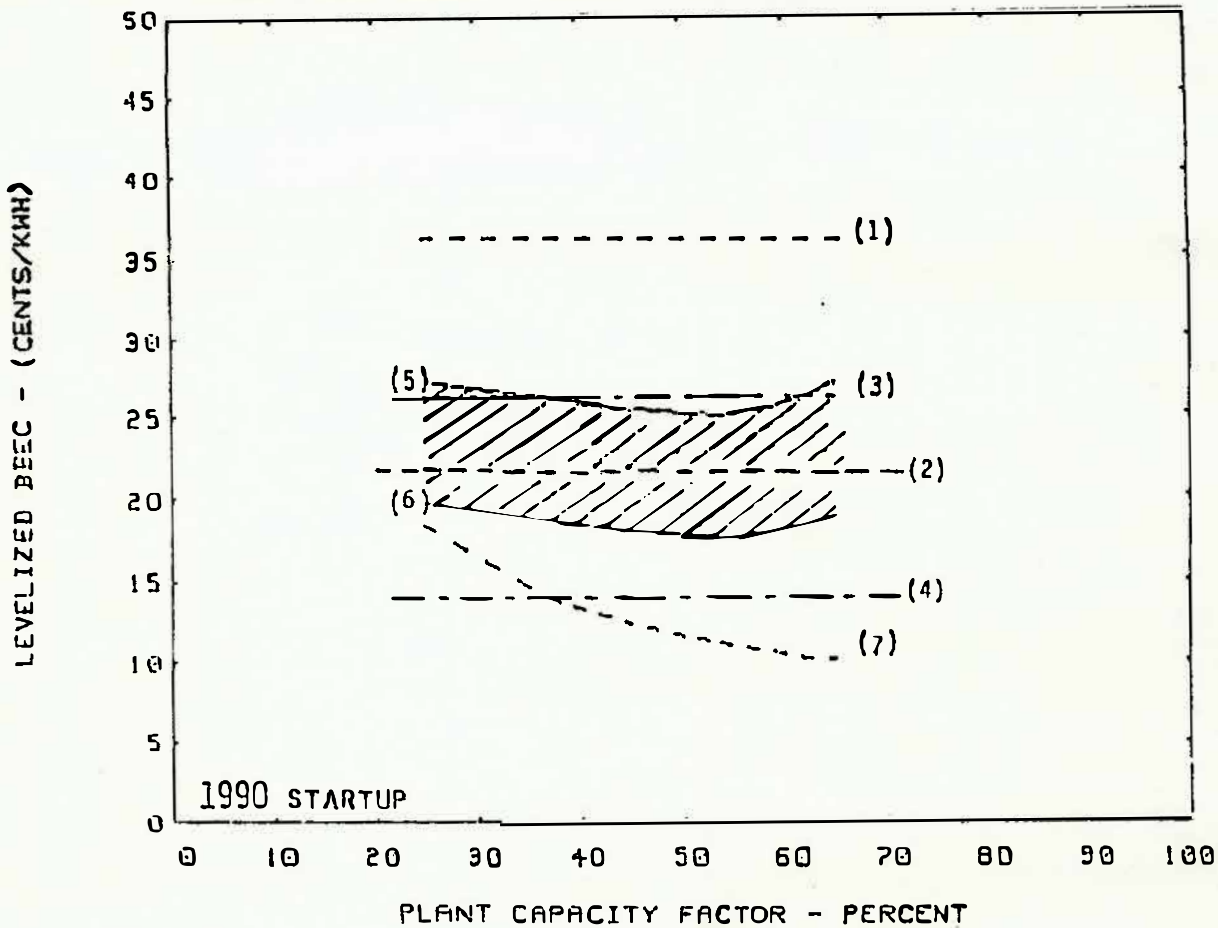
Fig. 5

LEVELIZED BBEC COMPARISONS



(1) No. 2 FUEL OIL – 11.9% ESCALATION
(2) No. 2 FUEL OIL – 8.9% ESCALATION
(3) No. 6 FUEL OIL – 11.9% ESCALATION
(4) No. 6 FUEL OIL – 8.9% ESCALATION
(5) SOLAR – ($216/m^2 – 1.5 x SOLAR COSTS)
(6) SOLAR – ($216/m^2)
(7) COAL – ($1200/kWe)

Fig.6

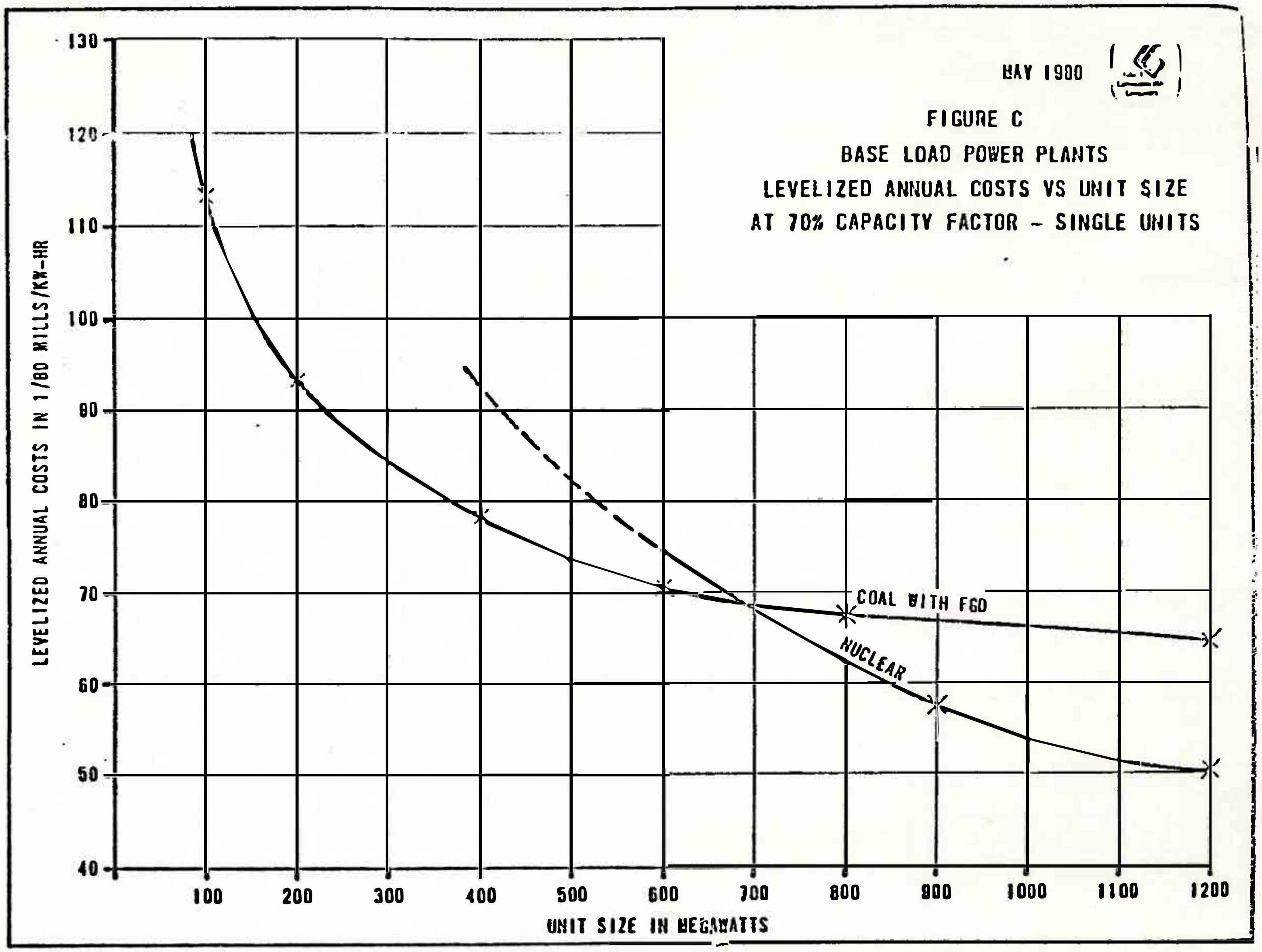

MAY 1980
FIGURE C
BASE LOAD POWER PLANTS
LEVELIZED ANNUAL COSTS VS UNIT SIZE
AT 70% CAPACITY FACTOR - SINGLE UNITS
LEVELIZED ANNUAL COSTS IN 1/80 MILLS/KW-HR
130
120
110
100
90
80
70
60
50
40
100
200
300
400
500
600
700
800
900
1000
1100
1200
UNIT SIZE IN MEGAWATTS
COAL WITH FGD
NUCLEAR

Fig. 7

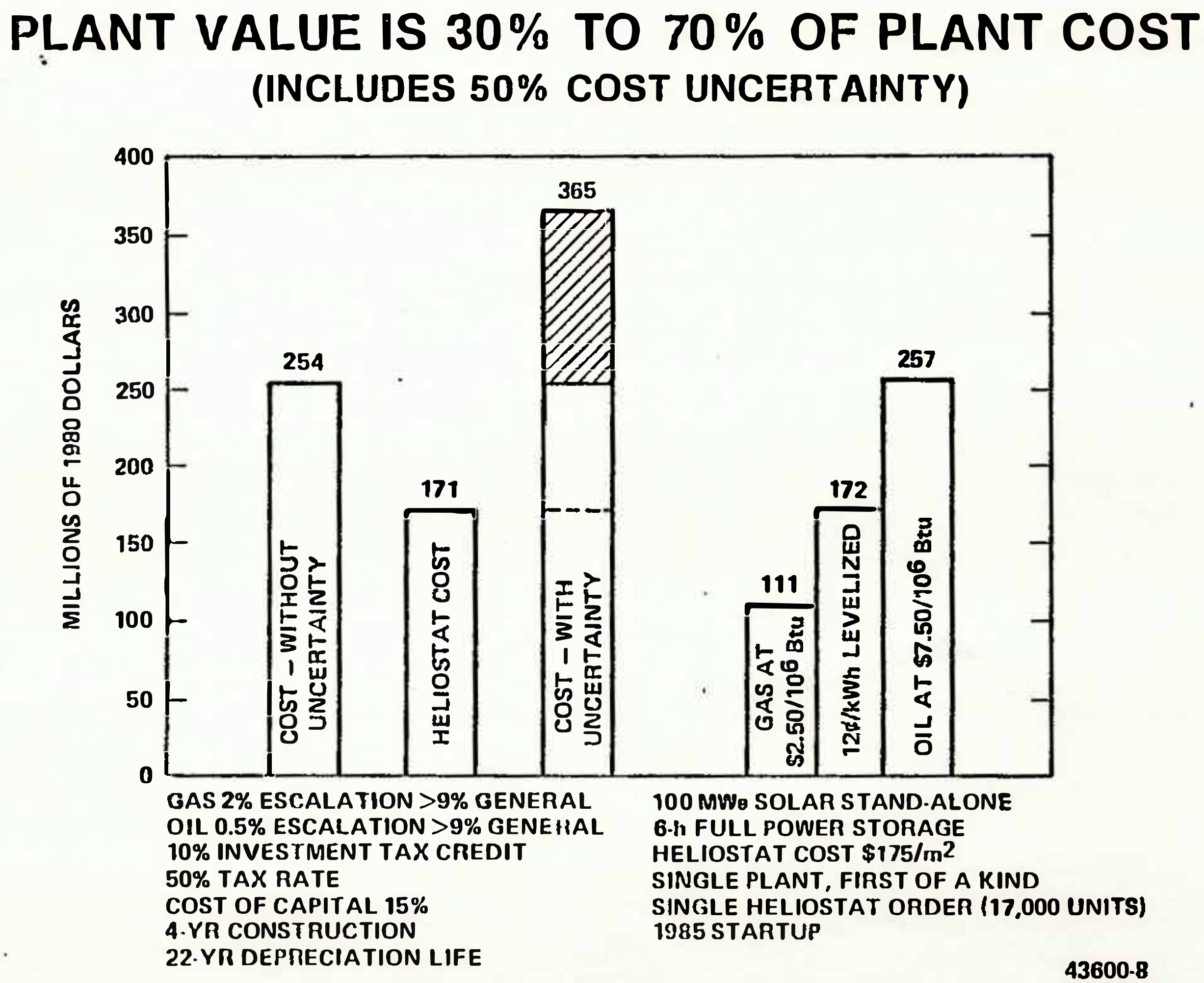

PLANT VALUE IS 30% TO 70% OF PLANT COST
(INCLUDES 50% COST UNCERTAINTY)
MILLIONS OF 1980 DOLLARS
400
350
300
250
200
150
100
50
0
254
COST – WITHOUT UNCERTAINTY
171
HELIOSTAT COST
365
COST – WITH UNCERTAINTY
111
GAS AT $2.50/10^6 Btu
172
12¢/kWh LEVELIZED
257
OIL AT $7.50/10^6 Btu
GAS 2% ESCALATION >9% GENERAL
OIL 0.5% ESCALATION >9% GENERAL
10% INVESTMENT TAX CREDIT
50% TAX RATE
COST OF CAPITAL 15%
4-YR CONSTRUCTION
22-YR DEPRECIATION LIFE
100 MWe SOLAR STAND-ALONE
6-h FULL POWER STORAGE
HELIOSTAT COST $175/m2
SINGLE PLANT, FIRST OF A KIND
SINGLE HELIOSTAT ORDER (17,000 UNITS)
1985 STARTUP
43600-8

Fig. 8