THE COMMERCIAL FEASIBILITY OF FUSION POWER BASED ON THE TOKAMAK CONCEPT*

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ABSTRACT

In this study we determine the impact of plasma operating characteristics, engineering options, and technology on the capital cost trends of tokamak power plants. Tokamak power systems are compared to other advanced energy systems and found to be economically competitive. A three-phase strategy for demonstrating commercial feasibility of fusion power, based on a common-site multiple-unit concept, is presented.

A. INTRODUCTION

The economic potential of tokamak power systems depends on technology, engineering, and plasma operating characteristics. In this study, we emphasize current technology which enhances the near-term feasibility of the tokamak concept. On this basis, the capital cost trends of tokamak power systems as a function of plasma operating conditions are investigated. The investigation is accomplished through the development of a computer model to scale plasma parameters and component cost.

B. THE MODEL

The model formulated to investigate the capital cost trends of tokamak power systems is composed of a plasma parameter scaling portion and a component cost scaling portion.

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1. Plasma Parameter Scaling

This portion of the model determines the required plasma radius and fields on axis for ignition and operation, given specific values of neutron wall loading, beta, aspect ratio, plasma elongation, and impurity level. Beta is defined as the ratio of average plasma pressure to magnetic field confining pressure and includes density and temperature profile effects. Plasma parameters are determined using both empirical and theoretical transport scaling relationships. The theoretical model is based on trapped particle scaling, described in Ref. 1, and is normalized to the plasma design values for The Next Step (TNS) given in Refs 2 and 3. The empirical scaling relationship $\tau \propto a^2n$, is normalized to the Massachusetts Institute of Technology (MIT) design for the High Field Compact Tokamak Reactor (HFCTR) described in Ref. 4. Empirical scaling, in general, describes plasmas which are thermally unstable. However, empirical scaling is included in this study to reflect the uncertainties in current plasma physics understanding.

Once the plasma size and field have been calculated, the remaining machine size and performance parameters are determined as follows. The major radius is the plasma radius times the specified aspect ratio. The toroidal field (TF) coil configuration is defined from the required field on axis, the space allowed for the blanket and shield (input value), an allowable current density, a required minimum ripple in the magnetic field at the plasma edge, and the specified coil elongation (ratio of vertical to horizontal bore). Thermonuclear power during the burn (14.1-MeV neutrons plus 3.5-MeV alpha particles) is determined from wall loading, plasma radius, major radius, and plasma elongation. Burn time is scaled as a function of plasma volt-seconds, plasma resistance, plasma current, and the flux swing capability of the ohmic heating (OH) coil. The flux swing of the OH coil depends on the specified field in the coil (set at 7 T for this study) and the bore of the OH winding, which in turn depends on the major radius and TF coil radius. Cycle average thermal power is computed from the burn time, the thermal power during the burn (thermonuclear power plus exothermic reactions in the blanket), and an assumed downtime of 1 min between cycles.

2. Component Cost Scaling

As previously indicated, current or near-term technology is emphasized. Table I shows the major systems for a tokamak power plant and the corresponding technology base used in this study. The component cost scaling portion

TABLE I. TECHNOLOGY BASE FOR MAJOR TOKAMAK POWER PLANT SYSTEMS

System	Technology Base
Magnetic	Superconducting ($NbTi$ and Nb_3Sn)
Plasma Heating	Neutral Beam Injection
Blanket Structure	Austenitic Stainless Steel
Tritium Handling	Cryopumping and Extracting
Pulsed Power Supplies	Motor Generator Flywheel Sets (∿500 MVA and ∿2 GJ)
Energy Conversion	Steam Cycle (T_s ∿750°F and η ∿35%)

of the model determines cost as a function of the system geometry and performance defined in the plasma parameter scaling portion of the code. Cost is determined by scaling existing cost estimates. The cost bases for the various components and the parameters used for cost scaling are presented in Table II.

TABLE II. COST BASES AND SCALING PARAMETERS FOR MAJOR TOKAMAK POWER PLANT COMPONENTS

Component	Cost Basis	Scaling Parameter
TF Coils	Large Coil Project	Coil Volume
MG Flywheel Sets	TFTR	Plasma Volt-seconds
Blanket and Heat Transport	Nuclear Industry	Blanket Volume; Thermal Power
Tritium Handling	Tritium Systems Test Assembly	Torus Surface Area
Neutral Beams	TFTR	Injected Power
Turbine	Equipment Vendors	$(\text{Thermal Power})^{0.8}$
Containment Building	NASA Vacuum Facility	Floor Area

C. COMPARISON OF TOKAMAK PARAMETERS USING TRAPPED PARTICLE AND EMPIRICAL SCALING

1. Normalizations

Using the plasma scaling portion of the model to generate plasma radii and fields on axis, the model was exercised to determine the variation of plant cost as a function of tokamak design parameters for ignited plasmas. Results were obtained assuming both trapped particle and empirical plasma scaling relationships. The trapped particle scaling relationship, as previously noted, was normalized to the TNS design while the empirical scaling relationship was normalized to an MIT conceptual design, the HFCTR. In addition, certain design parameters were held fixed, at either the respective TNS or HFCTR values, and are presented below.

a. Trapped Particle Study (Fixed Parameters)

a) Safety factor, $q = 3.0$
b) Electron temperature, $T_e = 14.6$ keV
c) Ion temperature, $T_i = 13.5$ keV
d) $Z_{eff} = 1.14$
e) Aspect ratio, $A = 4.0$
f) Plasma elongation, $\sigma = 1.6$
g) Distance from plasma edge to TF coil, $\Delta = 2.0$ m
h) Distance from plasma edge to first wall = 0.20 m

b. Empirical Study (Fixed Parameters)

a) Safety factor, $q = 3.0$
b) Electron temperature, $T_e = 7.5$ keV
c) Ion temperature, $T_i = 7.5$ keV
d) $Z_{eff} = 1.0$
e) Aspect ratio, $A = 5.0$
f) Plasma elongation, $\sigma = 1.6$
g) Distance from plasma edge to TF coil, $\Delta = 1.9$ m
h) Distance from plasma edge to first wall = 0.20

2. Unit Capital Cost

Unit capital cost, in dollars per kilowatt electric [$/kW(e)], is shown as a function of neutron wall loading and beta (constant A, σ, Δ) in Figs 1 and 2 for trapped particle and empirical scaling assumptions. These figures show that, regardless of which of these scaling relations is used, the unit capital cost of tokamak power systems lies in the range 1000-2000 \$/kW(e) (in 1976 dollars). This conclusion is based on achieving profile average values of beta of 5-10% which are high compared to values obtained in current experiments but are compatible with recent calculations of high beta tokamak operations [5].

Neutron wall loading initially has a strong effect on unit capital cost at a wall loading of $\sim$1 MW/m^2, but this effect diminishes with increased wall loading. Near-optimum plant cost is achieved at wall loadings in the range of 2-4 MW/m^2. It is suggested in Ref. 6 that wall lifetimes of approximately five years and more will not significantly reduce the plant capacity factor. Therefore, it appears that integral wall loadings of 10-20 MW-yr/m^2 would be adequate for the blanket structural material. It is noted that the curves of Figs 1 and 2 were generated for wall loadings between 1.0 MW/m^2 and 4.0 MW/m^2, or for that value of wall loading for which geometric constraints limit the design of the TF coils in the central bore region of the tokamak.

It should be noted that unit capital cost of Figs 1 and 2 is based on (1) direct capital cost (does not include engineering, contingency, interest during construction, etc.), (2) the thermal power level achieved during the burn portion of the tokamak cycle, and (3) a thermal-to-electric conversion efficiency of 35%.

3. Duty Factor

Consideration of the volt-second limitation on duty factor leads to a minimum in the unit capital cost curve, as shown in Fig. 3 for trapped particle scaling at a value of beta of 0.10. This minimum results from the rapid decrease of duty factor with wall loading, where duty factor is defined as the ratio of burn time to cycle time. Cycle time includes the downtime; for this study, downtime was assumed to be 1 min. Burn time depends on the volt-second capability of the OH coil which in turn is a function of the coil bore and the field in the coil, which was set at a value of 7 T for this study. Increasing the wall loading results in decreasing plasma radii (see Section C-4), which for a constant aspect ratio results in reduced machine bores and duty factors. Average unit capital cost is based on cycle average power where cycle average power is power during the burn times the duty factor. Average unit capital cost, therefore, goes through a minimum value as wall loading is increased and Fig. 3 shows that minimum average unit capital cost is achieved at a wall loading of approximately 3.0 MW/m^2 for trapped particle scaling.

4. Plasma Size and Field

The required plasma radius for self-sustaining operation is shown in Figs 4 and 5 as a function of beta and neutron wall loading for trapped particle and empirical scaling (for the particular sets of fixed design parameters under consideration). Note that increasing wall loading, at constant beta, results in decreasing plasma size. Regardless of which scaling law is used, a plasma size of 1-2 m is the range required for ignition in the economically interesting region of parameter space, i.e., beta of 5-10%, wall loading of 2-4 MW/m^2.

The required maximum fields, as a function of neutron wall loading and beta, are shown in Figs 5 and 6 for empirical and trapped particle scaling. The required range of maximum field consistent with the above region of parameter space is 6-11 T. These fields are low enough that Nb_3Sn superconductor may not be required in the toroidal field winding; thus, NbTi superconductor may be adequate for commercial fusion power. However, an additional consideration for Nb_3Sn is that it can be used at higher temperatures, thus providing greater stability and reduced refrigeration costs.

5. Power

Power levels in the range of 500-1000 MW(e) are characteristic of tokamak power systems, as shown in Fig. 7. Note that at constant beta, power decreases with increased wall loading. Recall from Fig. 3 that at constant beta, unit capital cost also decreases with increasing wall loading. The net effect is that, in contrast to fission reactors, unit capital costs for tokamak reactors do not necessarily favor larger power levels. This is shown graphically in Fig. 8, which is the 10% beta line from the unit capital cost curve of Fig. 3 with points from the power level curve of Fig. 7 superimposed. Fig. 8 shows that, at 10% beta, unit capital cost decreases as power level decreases from 1050 MW(e) to 825 MW(e), and then starts to increase as power is further reduced to 750 MW(e). (The minimum in the unit capital cost curve results from duty factor effects, as discussed in Section C-3).

D. SHARED FACILITIES AND MULTIPLE UNITS

For the purposes of this discussion, a representative set of parameters was chosen for a power reactor. This is not an optimized reactor, but one chosen from our study for illustration. The representative design parameters are presented in Table III.

TABLE III. DESIGN PARAMETERS FOR A TOKAMAK POWER REACTOR

Average Beta, β	0.10
Neutron Wall Loading, L	2.75 MW/m^2
Safety Factor, q	3.0
Aspect Ratio, A	4.0
Delta, Δ	2.0 m
Space between Plasma and First Wall	0.20 m
Plasma Radius, a	1.55 m
Plasma Elongation, σ_p	1.6
Field on Axis, B_T	3.4 T
Maximum Field at TF Coil, B_{max}	8.0 T
TF Coil Horizontal Bore	7.1 m
TF Coil Vertical Bore	9.6 m
TF Coil Elongation, σ_{TF}	1.35
Ripple (at Plasma Edge)	2%
Burn Time	23 min
Power (Burn), P_B	865 MW(e)
Power (Average), P_A	825 MW(e)
Duty Factor	0.95
Thermal Efficiency, η_T	$\sim$0.35

One of the major cost items for a tokamak reactor is the electrical plant, as indicated in Table IV. For this representative reactor design, the electrical plant constitutes approximately 25% of the total capital cost. The majority of the electrical plant cost is for the pulsed equipment

TABLE IV. CAPITAL COST (IN 1976 DOLLARS) FOR A REPRESENTATIVE TOKAMAK POWER REACTOR [SINGLE-UNIT PLANT PRODUCING 825 MW(e)]

SUBSYSTEM	COST (IN MILLIONS)
Reactor System	$ 280
Heat Transport System	111
Turbine System	86
Buildings	95
Electrical Plant	254
Other	127
TOTAL	$ 953
COST/kW(e) (Capital Only)	$1155 /kW(e)

required to induce current in the plasma and to heat the plasma to the ignition temperature. This is a cyclic operation and the expensive pulsed electrical plant of a tokamak power facility lies dormant during most of the cycle; therefore, the concept of multiple tokamak units tied into a common pulsed electrical plant appears attractive. Table V shows the effect on unit capital cost, $/kW(e), of clustering multiple reactor units.

TABLE V. UNIT CAPITAL COST IS SIGNIFICANTLY REDUCED BY SHARING PULSED ELECTRICAL EQUIPMENT

Number of Reactor Units	1	2	3
Power, MW(e)	825	1650	2475
$/kW(e)	1155	1020	974
% Unit Cost Decrease		12	16

E. COST COMPARISON WITH THE LMFBR

The capital cost of a liquid metal fast breeder reactor (LMFBR) prototype power plant was estimated based on the cost projection for the 975-MW(t)/350-MW(e) Clinch River Breeder Reactor Plant (CRBRP)[7]. The capital cost estimate for the CRBRP, in 1974 dollars, was $506 million, not including engineering and contingency costs. To escalate from mid-1974 dollars to mid-1976 dollars, a factor of 1.24 was used (based on the cost index data of the July 1976 Handy Whitman Bulletin). The cost of the CRBRP, now adjusted to mid-1976 dollars, is scaled assuming the capital costs vary as the 0.65th power of the thermal rating [7]. Taking 3800 MW(t)/1500 MW(e) as the appropriate size of the LMFBR prototype reactor plant, corresponding to the maximum rating of today's light-water reactor plants, the scaled cost of the LMFBR is $1484 million or $990/kW(e).

The cost of the 1500-MW(e) prototype LMFBR is compared in Table VI to two 825-MW(e) tokamak power reactors [1650 MW(e) total] sharing common pulsed electrical equipment. As a result of compensating component cost difference, tokamak and LMFBR prototypes achieve comparable unit capital costs, $1020/kW(e) for the tokamak as opposed to $990/kW(e) for the LMFBR.

TABLE VI. COMPENSATING COMPONENT COST DIFFERENCES BETWEEN TOKAMAK AND LMFBR PROTOTYPES RESULT IN COMPARABLE UNIT COSTS

Component	Tokamak Prototype	LMFBR Prototype
Reactor	340 [$/kW(e)]	230 [$/kW(e)]
Heat Transport	135	290
Electrical	170	50
Other	375	420
	1020 [$/kW(e)]	990 [$/kW(e)]

F. A STRATEGY FOR DEMONSTRATING COMMERCIAL FEASIBILITY

A three-phase program, built around a single-committed-site multiple-unit concept, offers a viable strategy for demonstrating commercial feasibility of tokamak fusion power. Commercial feasibility, in this context, means demonstrating the reliability and economic competitiveness of power generation under practical utility conditions. The three-phase program consists of (1) ignition demonstration (central pulsed electrical plant plus a single ignition device), (2) power technology demonstration (power conversion system added), and (3) commercial prototype demonstration (additional tokamak units added and tied to central pulsed electrical plant). We feel that such a strategy is rational because the plasma requirements for ignition are essentially the same as those associated with commercial plant operation. That is, plasma physics does not indicate that successively larger devices must be constructed proceeding from ignition to power demonstration and then to prototype commercial demonstration. Based on our cost estimates, it appears that such a program could be implemented in this century with a total facility cost of approximately $2-3 billion (in 1976 dollars). This does not include engineering and contingency costs, nor does it include development costs. When engineering, contingency, and development costs are included, the total facility cost is estimated to be $5-8 billion (in 1976 dollars). Escalation through the three-phase program results in an estimated facility cost in the range of $10-20 billion.

G. CONCLUSIONS

On the basis of these plant cost studies, it appears that the tokamak concept can lead to a power system with economic potential comparable to that of other advanced energy systems. In particular, this study has yielded the following conclusions:

1. Even with the current uncertainties in physics understanding, the estimated direct capital costs are ∿\$1000-2000/kW(e) (in 1976 dollars).

2. Plasma radii in the range of 1-2 m and maximum fields of 6-11 T are required.

3. The power output of tokamak reactors can be in the range of 500-1000 MW(e).

4. In contrast to fission reactors, unit capital costs for tokamak reactors do not necessarily favor larger power levels.

5. Multiple reactor units sharing common equipment can significantly reduce unit capital cost relative to the single reactor unit case.

6. Neutron wall loadings in the range of 2-4 MW/m^2 with material lifetimes of 10-20 $MW\text{-}yr/m^2$ will result in near-optimum plant costs.

7. A three-phase program, built around a single-site multiple-unit concept, offers a viable strategy for demonstrating the commercial feasibility of tokamak fusion power.

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(7) LEVENSON, M. et al., Economic perspective of the LMFBR, Nucl. News (April 1976).

FIGURE LEGENDS

1. Unit capital cost as a function of neutron wall loading and beta, assuming trapped particle scaling.

2. Unit capital cost as a function of neutron wall loading and beta, assuming empirical scaling.

3. Unit capital cost, based on both cycle average electrical power and electrical power during the burn, as a function of neutron wall loading at a value of beta of 0.10.

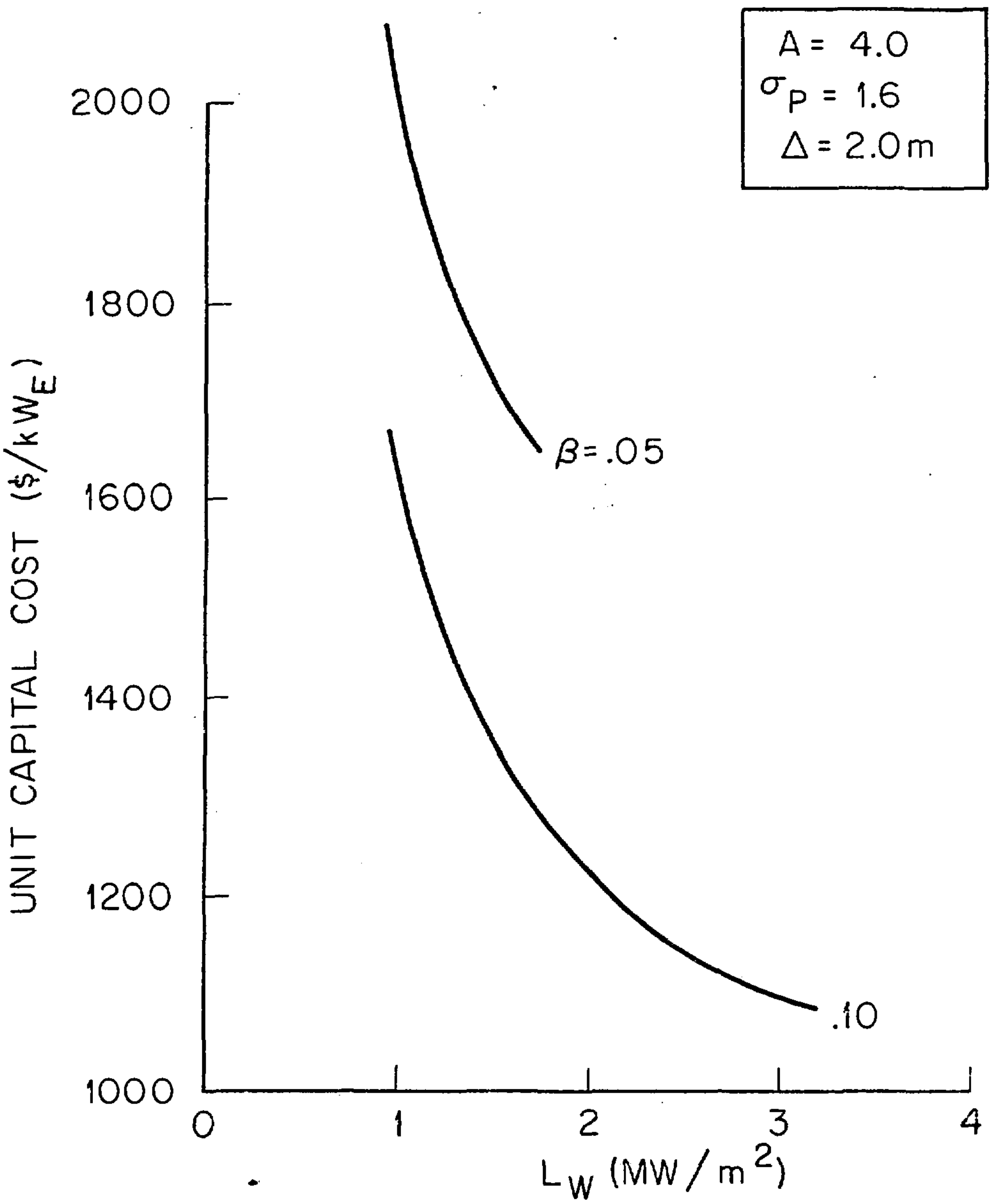
4. Required plasma radii for ignition, assuming trapped particle scaling, as a function of neutron wall loading and beta.

5. Required plasma radii and toroidal fields for ignition, assuming empirical scaling, as a function of neutron wall loading and beta.

6. Required toroidal fields for ignition, assuming trapped particle scaling, as a function of neutron wall loading and beta.

7. Cycle average power (solid lines) and power during the burn (dashed lines) as a function of neutron wall loading and beta for trapped particle scaling.

8. Unit capital cost initially decreases as power level decreases for a fixed value of beta.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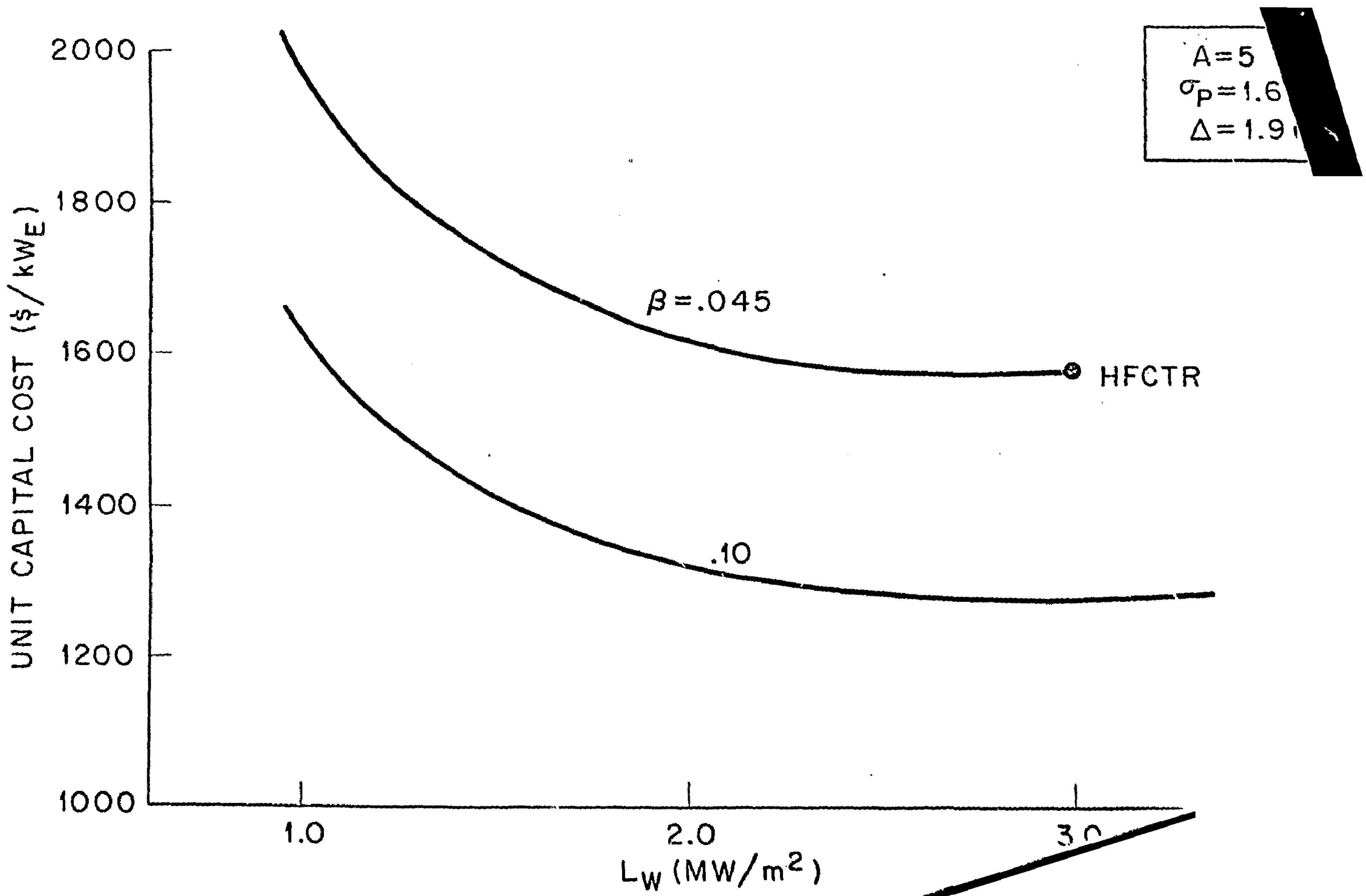
σP = 1.6
Δ = 2.0m
UNIT CAPITAL COST ($/kWE)
2000
1800
1600
1400
1200
1000
β=.05
.10
0
1
2
3
4
LW (MW/m2)

FIGURE 1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Δ=1.9
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β=.045
.10
HFCTR
2000
1800
1600
1400
1200
1000
UNIT CAPITAL COST ($/kW$_E$)
1.0
2.0
3.0
L_W (MW/m^2)

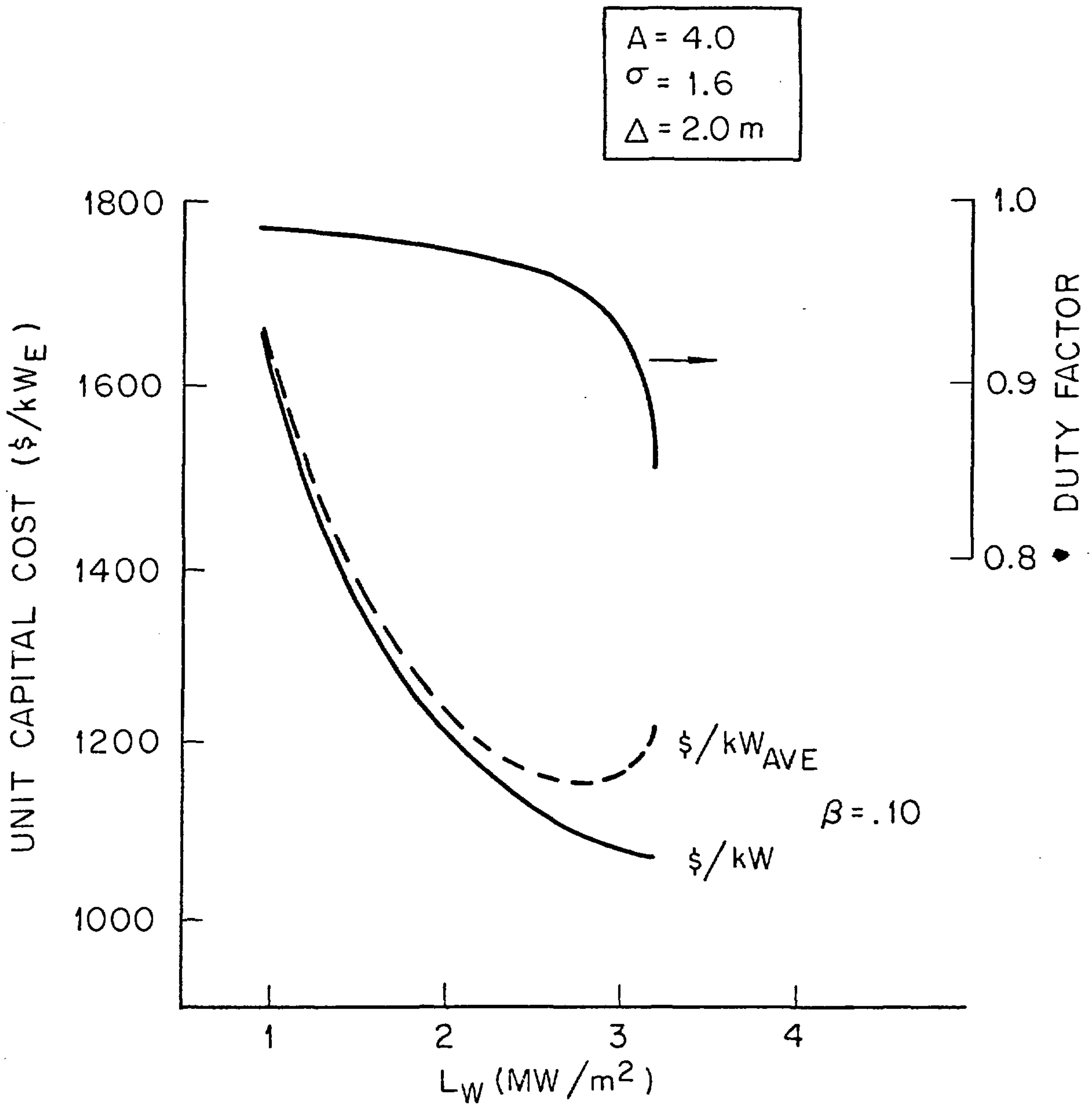

A = 4.0
σ = 1.6
Δ = 2.0 m
1800
1600
1400
1200
1000
UNIT CAPITAL COST ($/kW_E)
1.0
0.9
0.8
DUTY FACTOR
$/kW_AVE
β = .10
$/kW
1
2
3
4
L_W (MW/m²)

FIGURE 3

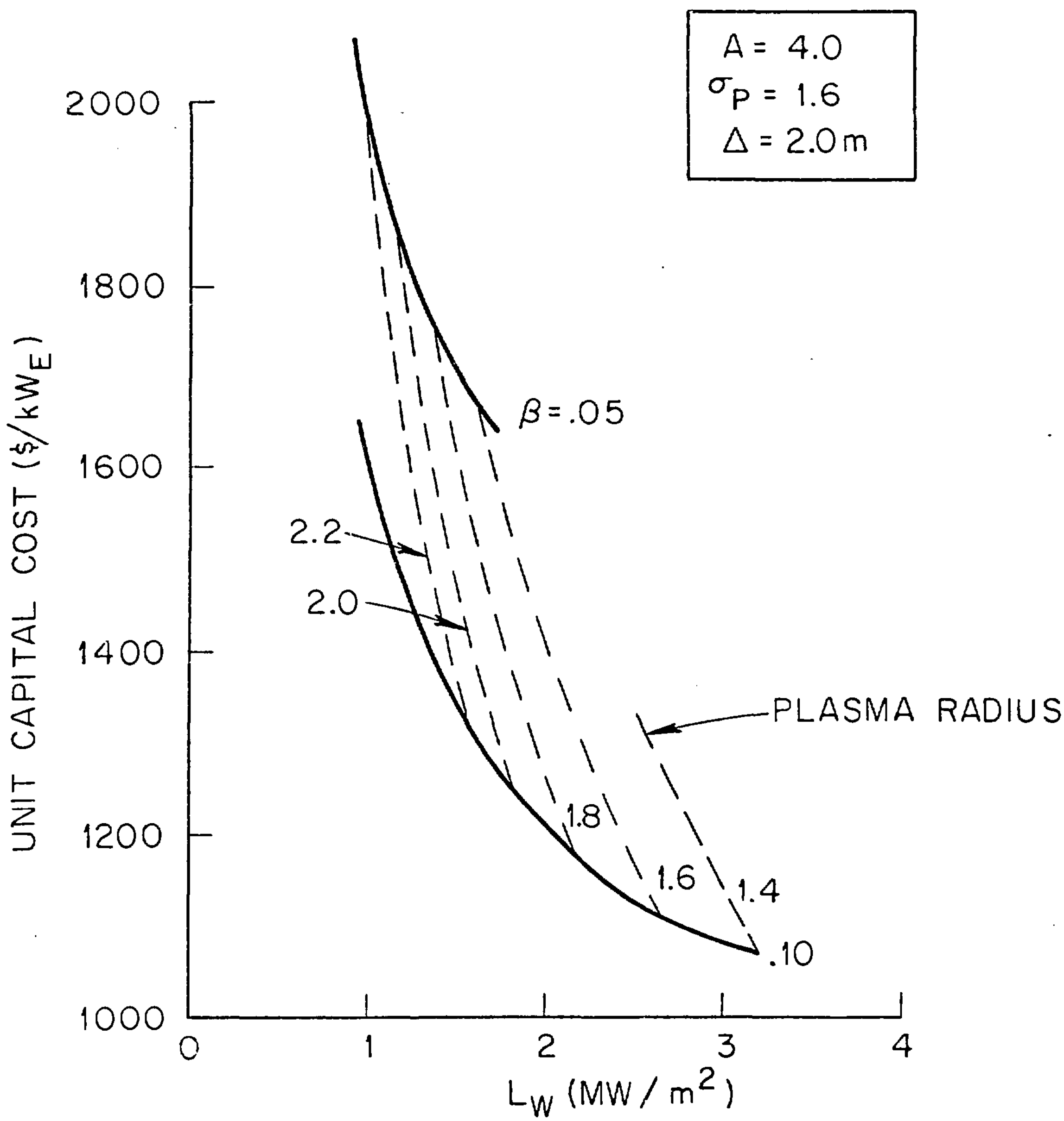

A = 4.0
σ_P = 1.6
Δ = 2.0 m
UNIT CAPITAL COST ($/kW$_E$)
2000
1800
1600
1400
1200
1000
β = .05
2.2
2.0
1.8
1.6
1.4
.10
PLASMA RADIUS
0
1
2
3
4
L_W (MW / m^2)

FIGURE 4

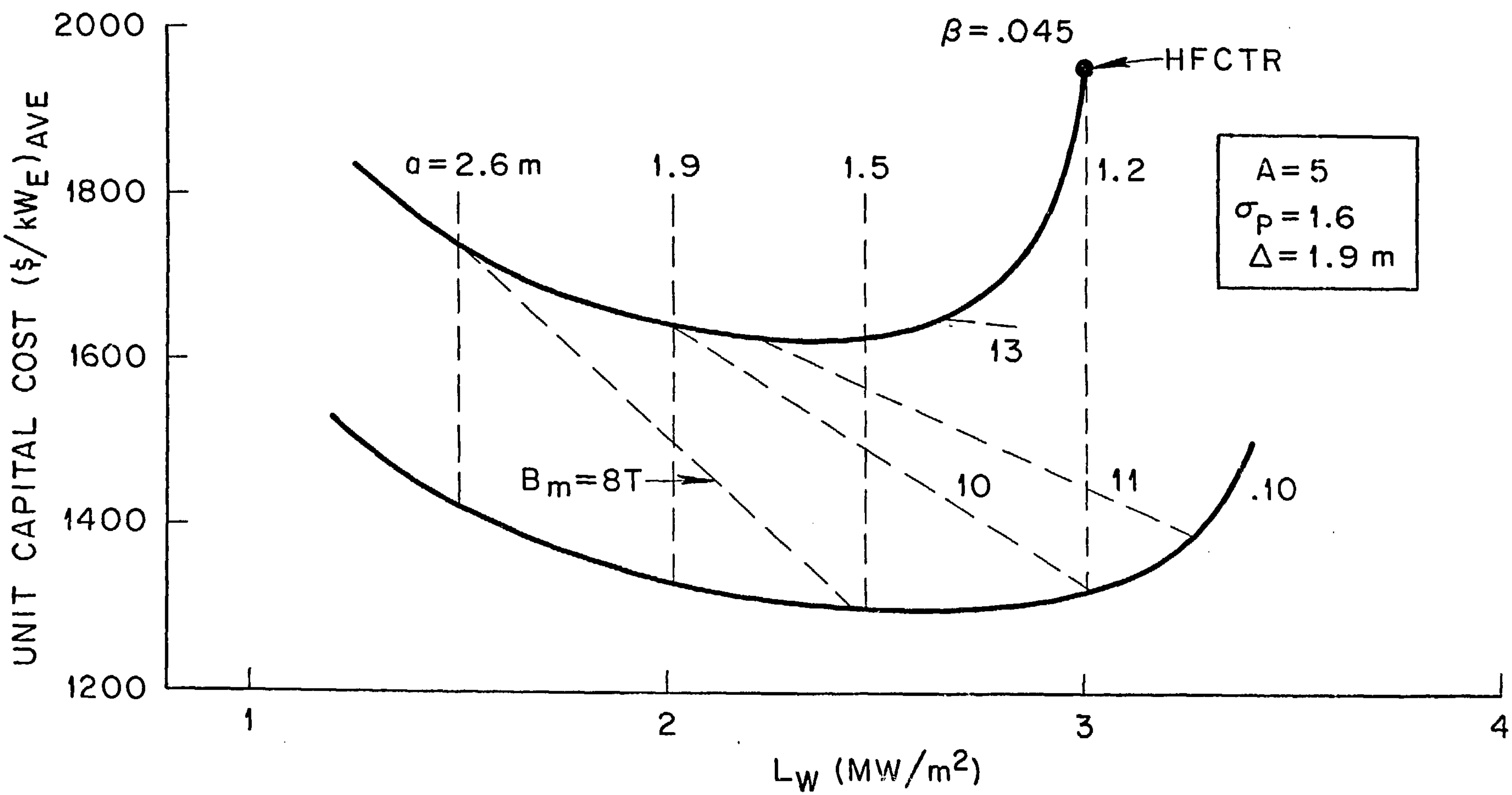
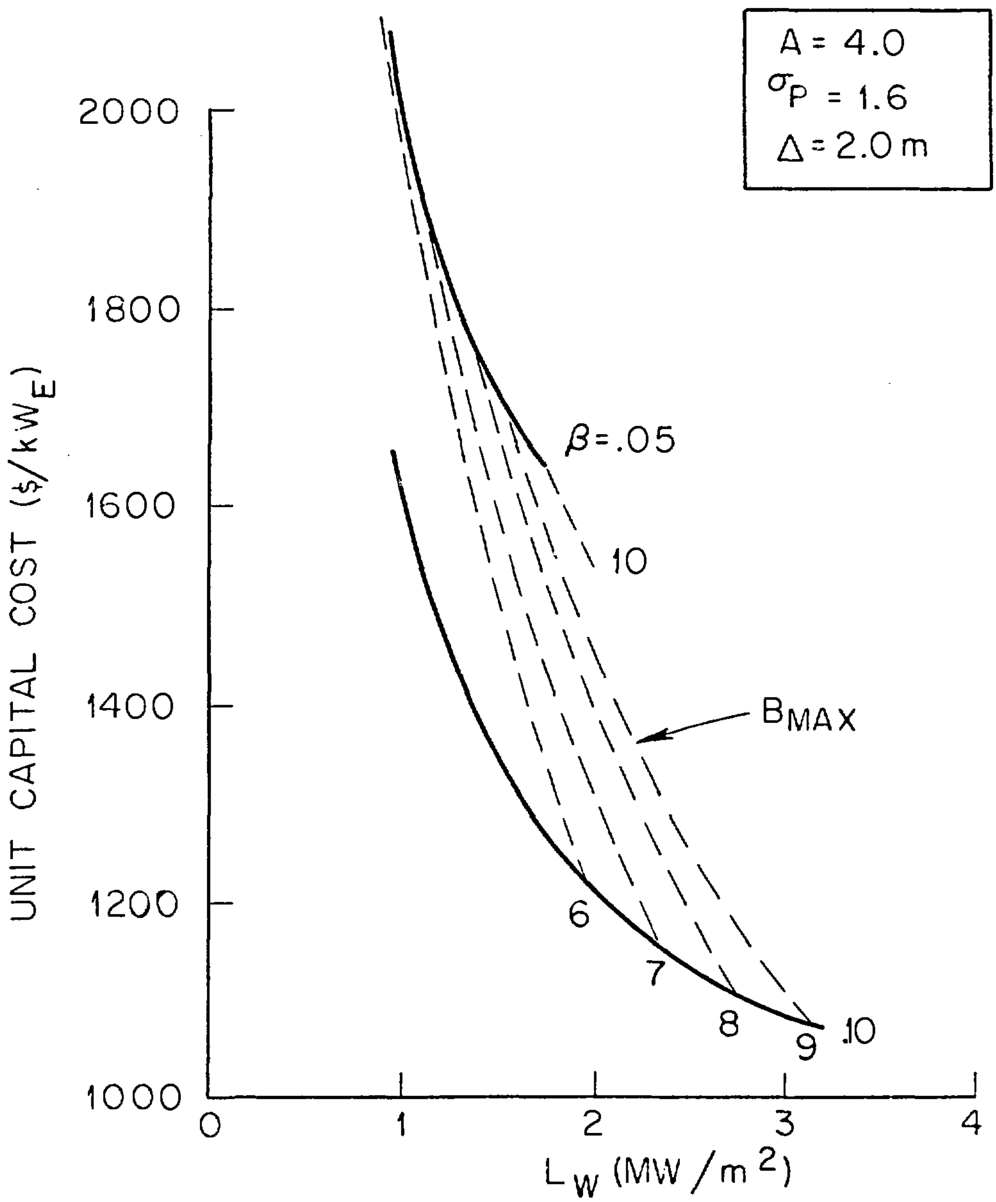

β=.045
HFCTR
A=5
σp=1.6
Δ=1.9 m
a=2.6 m
1.9
1.5
1.2
13
10
11
.10
Bm=8T
2000
1800
1600
1400
1200
UNIT CAPITAL COST ($/kWE)AVE
1
2
3
4
LW (MW/m2)

FIGURE 5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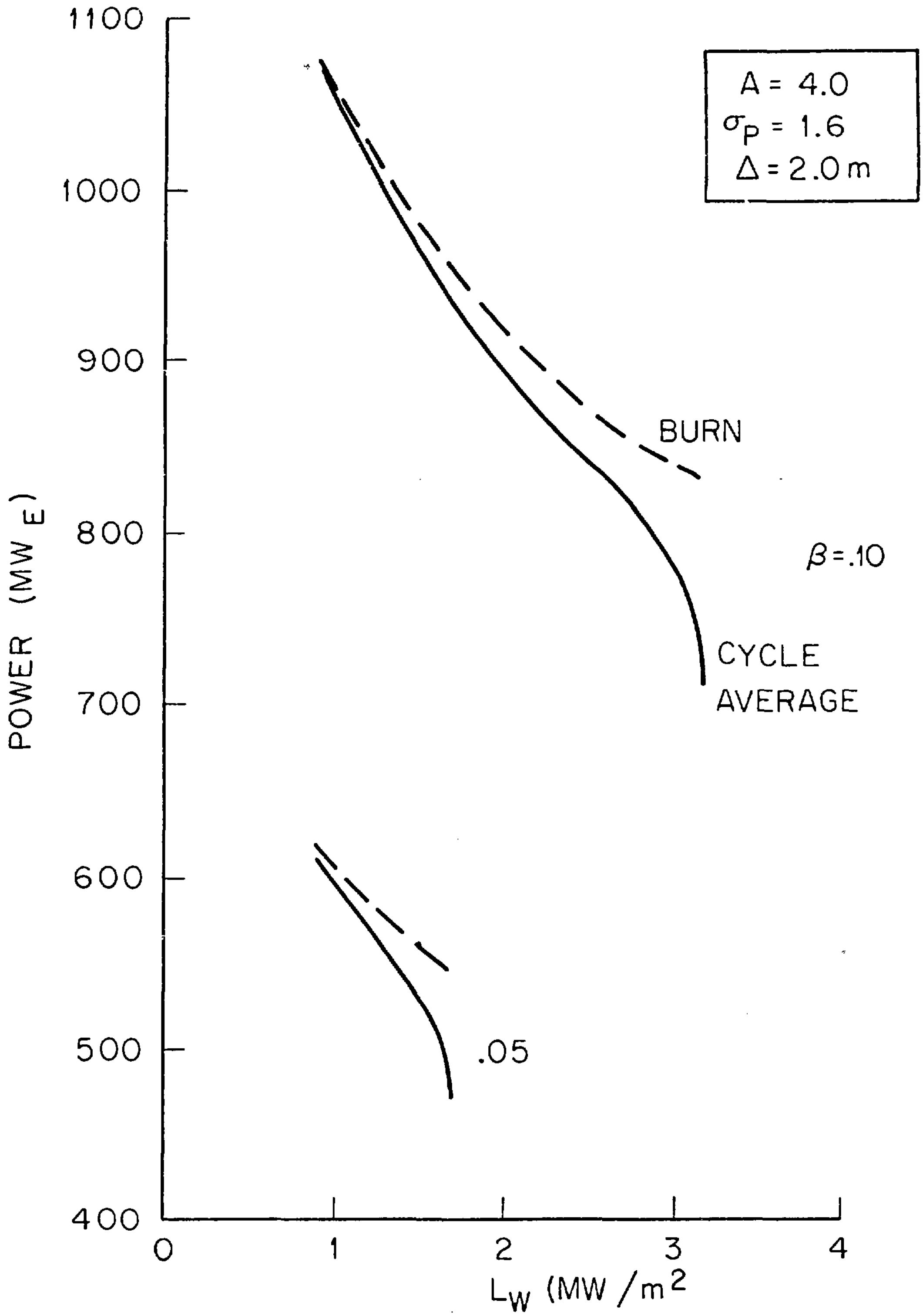
σP = 1.6
Δ = 2.0 m
2000
1800
1600
1400
1200
1000
UNIT CAPITAL COST ($/kWE)
β = .05
.10
BMAX
6
7
8
9
.10
0
1
2
3
4
LW (MW/m 2)

FIGURE 6



A = 4.0
σ_P = 1.6
Δ = 2.0 m
BURN
β = .10
CYCLE
AVERAGE
.05
1100
1000
900
800
700
600
500
400
POWER (MW_E)
0
1
2
3
4
L_W (MW / m^2

FIGURE 7

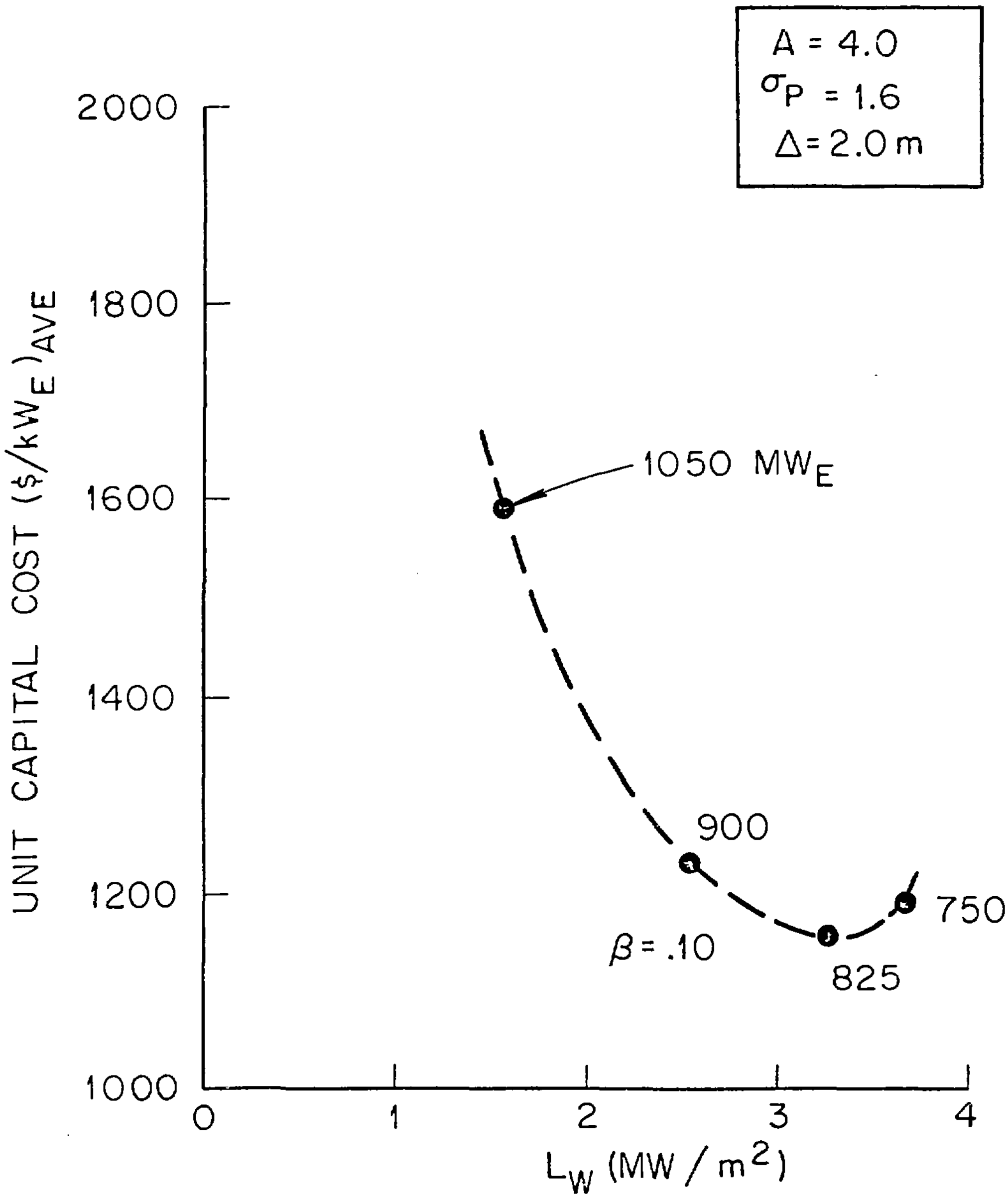

A = 4.0
σP = 1.6
Δ= 2.0 m
2000
1800
1600
1400
1200
1000
UNIT CAPITAL COST ($/kWE)AVE
1050 MWE
900
825
750
β = .10
0
1
2
3
4
LW (MW / m2)

FIGURE 8