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ECONOMIC TRENDS OF TOKAMAK POWER PLANTS INDEPENDENT OF PHYSICS SCALING MODELS*

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This study examines the effects of plasma radius, field on axis, plasma impurity level, and aspect ratio on power level and unit capital cost, $\$/kW_e$, of tokamak power plants sized independent of plasma physics scaling modesl. It is noted that tokamaks sized in this manner are thermally unstable based on trapped particle scaling relationships. It is observed that there is an economic advantage for larger power level tokamaks achieved by phsyics independent sizing; however, the incentive for increased power levels is less than that for fission reactors. It is further observed that the economic advantage of these larger power level tokamaks is decreased when plasma thermal stability measures are incorporated, such as by increasing the plasma impurity concentration. This trend of economy with size obtained by physics independent sizing is opposite to that observed when the tokamak designs are constrained to obey the trapped particle and empirical scaling relationships.

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INTRODUCTION

In a previous study[1], the capital cost trends of ignited tokamak power systems were investigated using both trapped particle and empirical scaling relationships. These scaling models specify a unique combination of size and field on axis for given values of neutron wall loading and beta. This is a consequence of two equations and two unkowns: (1) the physics scaling relationship between $N_e\tau_E$, size, field, and beta required for ignition at a fixed plasma temperature and (2) the relationship between wall loading, size, field, and beta. In the current study, capital cost is examined independent of physics scaling models; thus, the constraint between $N_e\tau_E$, size, field, and beta at a given temperature is eliminated. Since there is now only one equation and two unknowns, for fixed wall loading and beta, there is no longer a unique combination of size and field; in fact any number of combinations of values are possible.

EFFECT OF SIZE AND FIELD ON PERFORMANCE

Figure 1 shows unit capital cost,† $\$/kW_e$, as a function of neutron wall loading for various combinations of plasma size and field on axis at a volume average balue of beta of 0.10 and an aspect ratio of 4.0. This figure shows that unit capital cost decreases as neutron wall loading. Also, this figure shows that increasing the plasma size while decreasing the field on axis, at a given value of neutron wall loading, results in a decreasing unit capital cost. Superimposed on Fig. 1 is the variation of unit capital cost with wall loading assuming trapped

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† Cost estimation for this study is based on the cost scaling model described in Ref. 1.

particle plasma scaling relationships. Based on trapped particle scaling, points in parameter space lying above this line represent plasmas which fail to ignite, while points lying below this line represent plasmas which will experience a thermal runaway. In order to operate a tokamak in the region of parameter space characterized by increased plasma sizes and decreased fields relative to those required for trapped particle scaing, a feedback control system or some type of impurity injection scenario must be assumed. The cost and complexity of this plasma control mechanism will reduce the economic advantage (indicated in Fig. 1) of operating tokamaks at thermally unstable plasma conditions.

As shown in Ref. 1, unit capital cost for tokamak power plants decreases with decreasing power level when trapped particle scaling is assumed. However, if scaling laws are ignored, and one trades increased plasma size for decreased field at a given wall loading, beta, and aspect ratio, then unit capital cost decreases as power level increases, as shown in Fig. 2. Even ignoring the plasma thermal stability problem, the incentive for operating tokamak power plants at higher power levels is not as great as is the case for fission reactor plants, as shown in Fig. 2, where capital cost for fission plants typically varies as the 0.65 exponent of power level.

EFFECT OF PLASMA IMPURITY ON PERFORMANCE

The effect of operating a tokamak in the thermally unstable region of parameter space by injecting impurities to achieve a plasma power balance was determined. Typical results are shown in Fig. 3. This figure shows unit capital cost, $\$/kW_e$, as a function of neutron wall loading for a fixed plasma size of 2.0 m, a volume average value of beta of 0.10, an aspect ratio of 4.0, a plasma temperature of 14 keV, and an

impurity atomic number of Z = 6 (carbon). Two curves are shown on this figure. The solid line is for a fixed Z_{eff} of 1.1 and is for a plasma which is thermally unstable based on trapped particle scaling (this is the same line as the a = 2.0 m line in the thermal runaway region of parameter space shown in Fig. 1). The dashed line on Fig. 3 is for a plasma which is thermally stable with the stability achieved by increasing the values of Z_{eff} to the values indicated on the curve. One notes that increasing Z_{eff} from a value of 1.1 to 2.5 results in increasing values of unit capital cost, while further increase in Z_{eff} results in decreasing values of unit capital cost up to a limiting value of Z_{eff} of approximately 3.4 where self-sustaining plasma operation ceases. The consequence of achieving plasma thermal stability by increased impurity concentration is to increase the unit capital cost of the tokamak power plant relative to the thermally unstable (physics independent) design. See the Appendix for a more in-depth discussion of impurity effect on performance.

The economic advantage of operating in the physics independent region of parameter space may be negligible when plasma control mechanisms are accounted for as is indicated in the following example. The value of unit capital cost for a thermally stable, clean tokamak power plant (Z_{eff} = 1.1) with a plasma size of 1.5 m at a neutron wall loading of 2.85 MW/m^2 is \$1100/kW_e as shown in Fig. 1. Now, increasing the plasma size to 2.0 m at the same wall loading reduces the unit capital cost to 990 \$/kW_e, as shown in Fig. 1 and the dashed line of Fig. 3, if thermally unstable plasma operation is allowed. However, the penalty to achieve thermal stability (based on trapped particle theory) in a tokamak at the increased plasma size of 2.0 m at a 2.85-MW/m^2 neutron wall loading by

increasing the impurity concentration ($Z_{eff} \sim 3.2$) results in an increase in unit capital cost to a value of 1075 $\$/kW_e$ as shown by the dashed curve of Fig. 3. This results in a net advantage of only 25 $\$/kW_e$ for a larger ($a = 2.0$), dirtier ($Z_{eff} \sim 3.2$) tokamak relative to a smaller ($a = 1.5$), cleaner ($Z_{eff} = 1.1$) tokamak power plant for the set of fixed parameters used in this example. An additional disadvantage of the large, dirty machine is that plasma ignition is very sensitive to Z_{eff} in this regime of operation, and a slight increase of Z_{eff} from 3.2 to 3.4 will extinguish the plasma.

EFFECT OF ASPECT RATIO ON PERFORMANCE

The effect of aspect ratio on tokamak power plant cost and performance was determined assuming both trapped particle scaling relationships and physics independent modeling. Typical results are presented in Figs. 4 and 5 for constant values of neutron wall loading and beta.

Figure 4 shows the relationship of aspect ratio to unit capital cost and power output assuming trapped particle scaling. In the Appendix of Ref. 1, plasma radius is seen to vary inversely as aspect ratio for fixed values of beta and neutron wall loading. Power output during the burn portion of a tokamak operating cycle can also be expressed as a function of plasma radius squared times the aspect ratio for a fixed value of neutron wall loading. The net effect is that power output is inversely proportional to the aspect ratio for fixed wall loading and beta as is demonstrated by the solid curve of Fig. 4. As the aspect ratio decreases from a value of 6 to 3, power increases from approximately 600 MW_e to 1200 MW_e and unit capital cost decreases from 1300 $\$/kW_e$ to

about 1150 $/kW$_e$. However, the decreasing aspect ratio provides a smaller inner torus radius and therefore a decreased volt-second capability for the ohmic heating transformer. A decrease in volt-seconds reduces plasma burn time and duty factor which results in a decrease in cycle average power. The net result is that an aspect ratio of approximately 4.0 is optimum based on unit capital cost computed using cycle average power (dashed line in Fig. 4). The power level at this optimum aspect ratio is approximately 850 MW$_e$ (for a neutron wall loading of 2 MW/m^2 and a value of beta of 0.10).

Figure 5 shows the effect of aspect ratio on unit capital cost and power independent of physics restrictions. This curve is for a fixed neutron wall loading of 2.75 MW/m^2, a plasma radius of 1.55 m, a field on axis of 3.4 T, and a value of beta of 0.10. Increasing the aspect ratio from 4 to 6 results in increasing the power level from approximately 800 MW$_e$ to 1300 MW$_e$ and reducing unit capital cost from 1100 to 1000 $/kW$_e$. The net effect is that there is an economy with scale for a tokamak power plant assuming physics independent sizing but the effect is slight; a 10% reduction in unit capital cost for a 65% increase in power level. In addition, the value of beta was not degraded with increasing aspect ratio as current plasma physics suggests, which would reduce the economic advantage of the higher aspect ratio and higher power levels.

CONCLUSIONS

1. Tokamak power plants sized based on trapped particle and empirical physics scaling models show an increase in unit capital cost as power level is increased for fixed values of beta and aspect ratio.

2. Tokamak power plants sized independently of physics scaling models show some economic advantage of higher power levels but less than that for fission power plants.

3. Tokamak power plants sized independently of physics scaling models lose some of their economic advantage when plasma thermal stability measures are incorporated.

4. Based on the cost model and the assumptions used in this study, there appears to be little incentive for sizing tokamak units for power levels greater than 1000 MW_e.

APPENDIX

This section is included to expand the discussion of impurity effects on performance and cost of tokamak power systems presented in the section of this paper, EFFECT OF PLASMA IMPURITY ON PERFORMANCE.

Assumptions

1. $T_{ion} = T_{electron}$ (ion temperature = electron temperature).

2. $N_{\alpha} = 0.05\ N_e$ (alpha particle density is 5% of electron density).

3. Plasma is electrically neutral.

4. Single species impurity.

5. Plasma is ignited and is in thermal equilibrium (power from alpha particles balance conduction, convection and radiation losses).

Fixed parameters for the following are:

$a = 1.5$ m	Plasma radius
$A = 4.0$	Aspect ratio
$\sigma = 1.6$	Plasma elongation
$\beta = 0.10$	Profile average beta
$T = 14$ keV	Plasma temperature
$Z = 6$	Atomic number of impurity element

From the plasma energy balance, the required $N_e\tau_E$ can be expressed as a function of the specified plasma temperature, Z_{eff}, and the impurity Z. As Z_{eff} is varied for fixed temperature and impurity element the required $N_e\tau_E$ varies as shown in Fig. A-1. $N_e\tau_E$ initially increases slowly with increasing Z_{eff} but around a value of Z_{eff} of 2.5 $N_e\tau_E$ increases rapidly with Z_{eff} up to a value of Z_{eff} of approximately 3.4 at which point self-sustaining plasma operation ceases.

As the impurity level rises in the plasma, as indicated by increasing values of Z_{eff}, the portion of the fixed total average beta contributed by the fuel ions, β_{ion}, decreases as also shown in Fig. A-1.

Field on axis can be computed from the following trapped particle scaling relationship:

$$N_e\tau_E \propto a^4\beta^2 B_T^6 A^{2.5} Z_{eff} \frac{1}{T}^{5.5}(1 + \sigma^2)$$

since for this example all parameters except B_T are fixed. The required $N_e\tau_E$ for the above equation is that value shown in Fig. A-1 as a function of Z_{eff}. If $N_e\tau_E$ increases more than the increase in Z_{eff}, the field on axis, B_T, will increase; otherwise it will decrease. As noted on Fig. A-1, B_T decreases with increasing Z_{eff} up to a value of Z_{eff} of approximately 1.5 and then increases with further increases in Z_{eff}.

Power density, MW/m^3, is a function of $\beta b_{ion}^2 \times B_T^4$. Since β_{ion} is a decreasing function of increasing Z_{eff} and B_T is both a decreasing and an increasing function of Z_{eff}, the power density goes through a minimum with increasing Z_{eff} as shown in Fig. A-1.

The effect of power density going through a minimum is reflected in unit capital cost going through a maximum as indicated in Fig. A-2. Neutron wall loading as a function of Z_{eff} is also shown in Fig. A-2. Neutron wall loading varies in a similar manner as the power density.

Figure A-3 shows the variation in electron density, N_e, ion density, N_i, and confinement time, τ_E, as a function of Z_{eff}.

REFERENCES

1. Steiner, D. et al., "ORNL Fusion Power Demonstration Study: Interim Report," ORNL/TM-5813, March, 1977.

FIGURE LEGENDS

FIGURE 1. Capital cost can be reduced below levels predicted by trapped particle scaling given plasma thermal stability.

FIGURE 2. Fusion plant cost is less sensitive to power level than is fission plant cost (constant aspect ratio).

FIGURE 3. Providing thermal stability reduces the economic advantage of physics independent tokamak sizing.

FIGURE 4. At a given value of neutron wall loading and beta, unit capital cost optimizes with tokamak power level (trapped particle scaling).

FIGURE 5. Fusion plant cost is less sensitive to power level than is fission plant cost (variable aspect ratio).

FIGURE A-1. Plasma performance as a function of Z_{eff}.

FIGURE A-2. Unit capital cost and wall loading as a function of Z_{eff}.

FIGURE A-3. Energy confinement time, electron density, and fuel ion density as a function of Z_{eff}.

FIGURE 1.

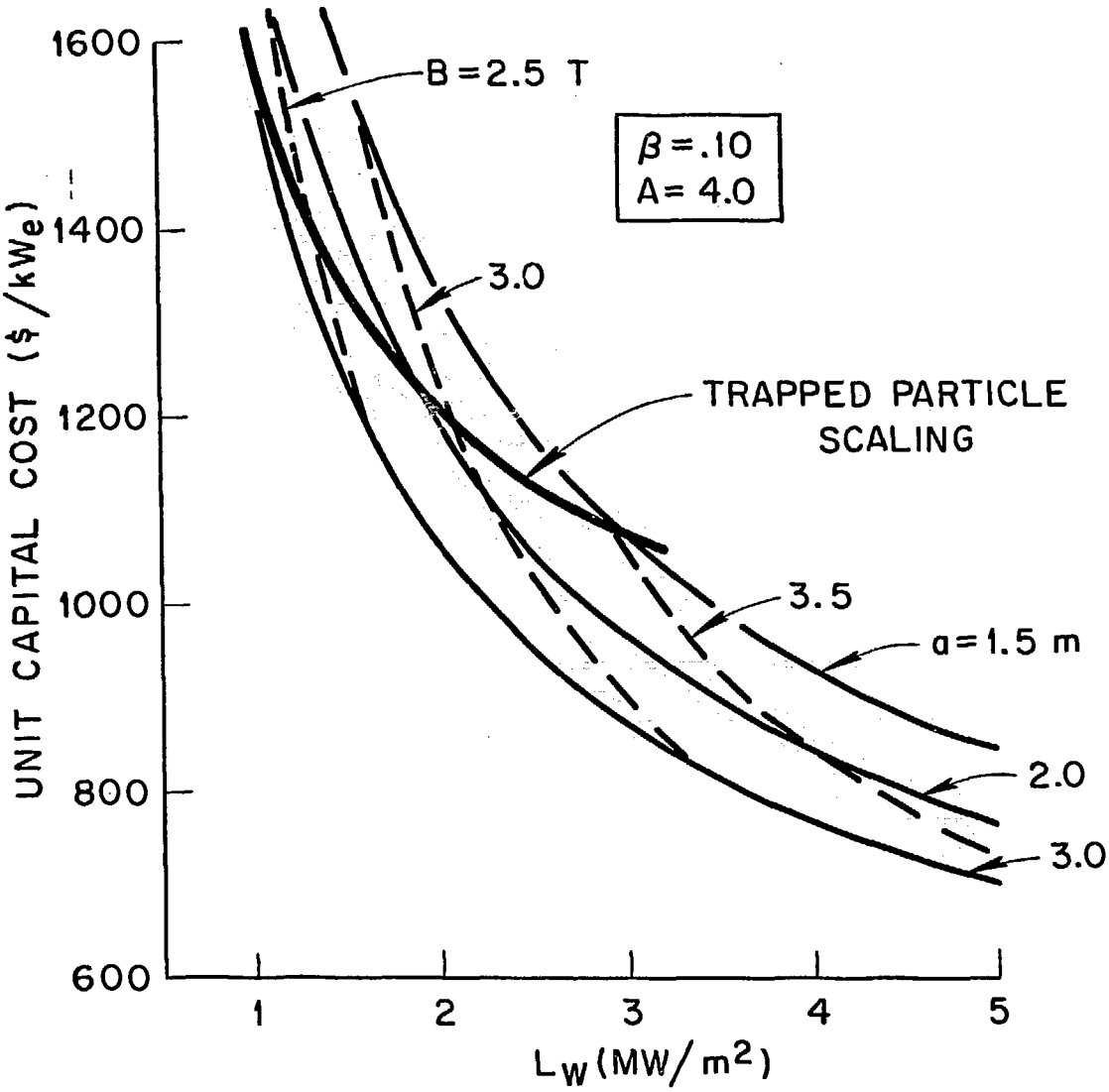

1600
1400
1200
1000
800
600
UNIT CAPITAL COST ($/kWe)
1
2
3
4
5
Lw (MW/m2)
B = 2.5 T
β = .10
A = 4.0
3.0
TRAPPED PARTICLE
SCALING
3.5
a = 1.5 m
2.0
3.0

FIGURE 2.

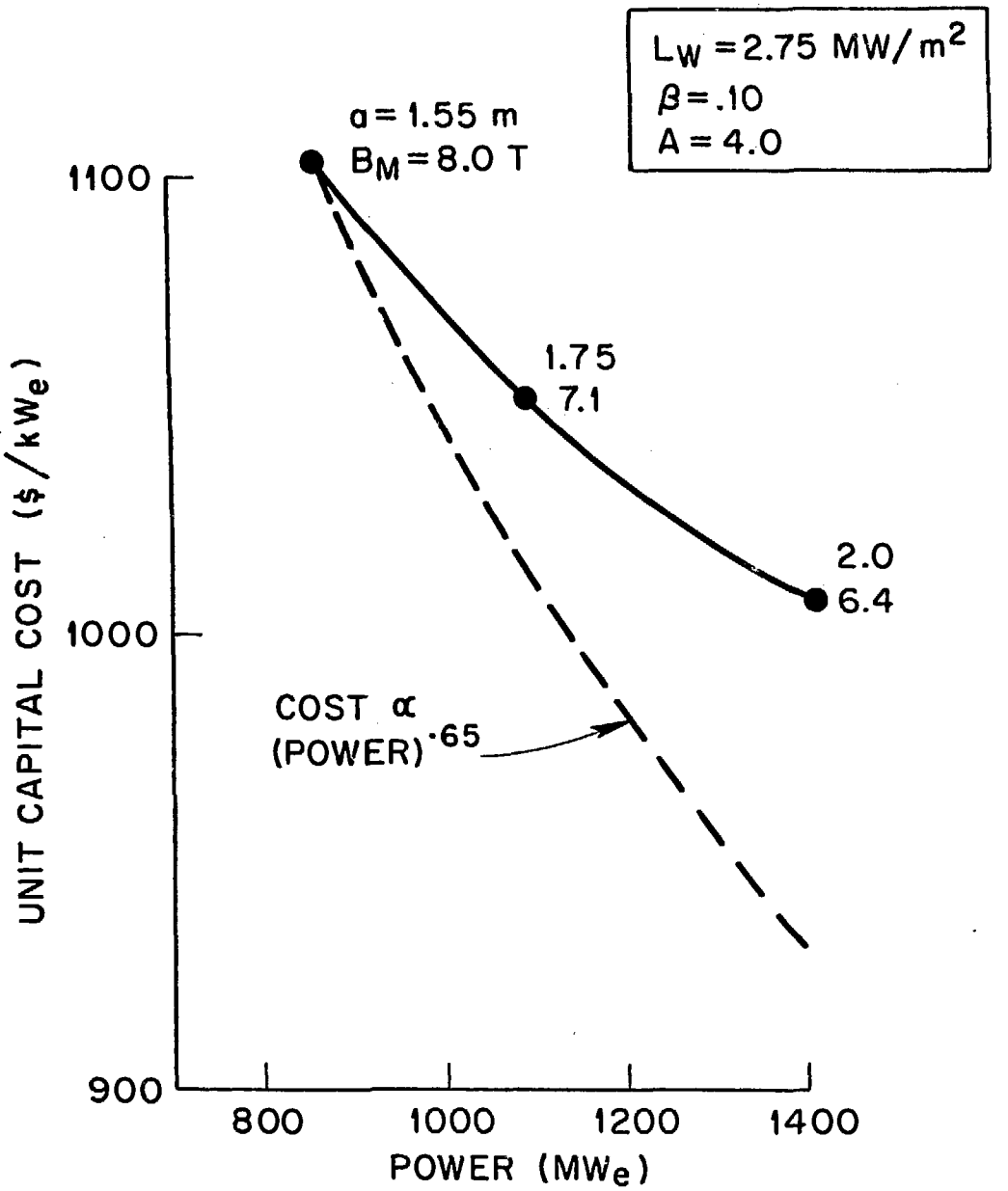

$L_W = 2.75$ MW/m^2
$\beta = .10$
$A = 4.0$
$a = 1.55$ m
$B_M = 8.0$ T
1.75
7.1
2.0
6.4
COST α (POWER)$^{.65}$
UNIT CAPITAL COST ($/kW$_e$)
1100
1000
900
800
1000
1200
1400
POWER (MW$_e$)

FIGURE 3.

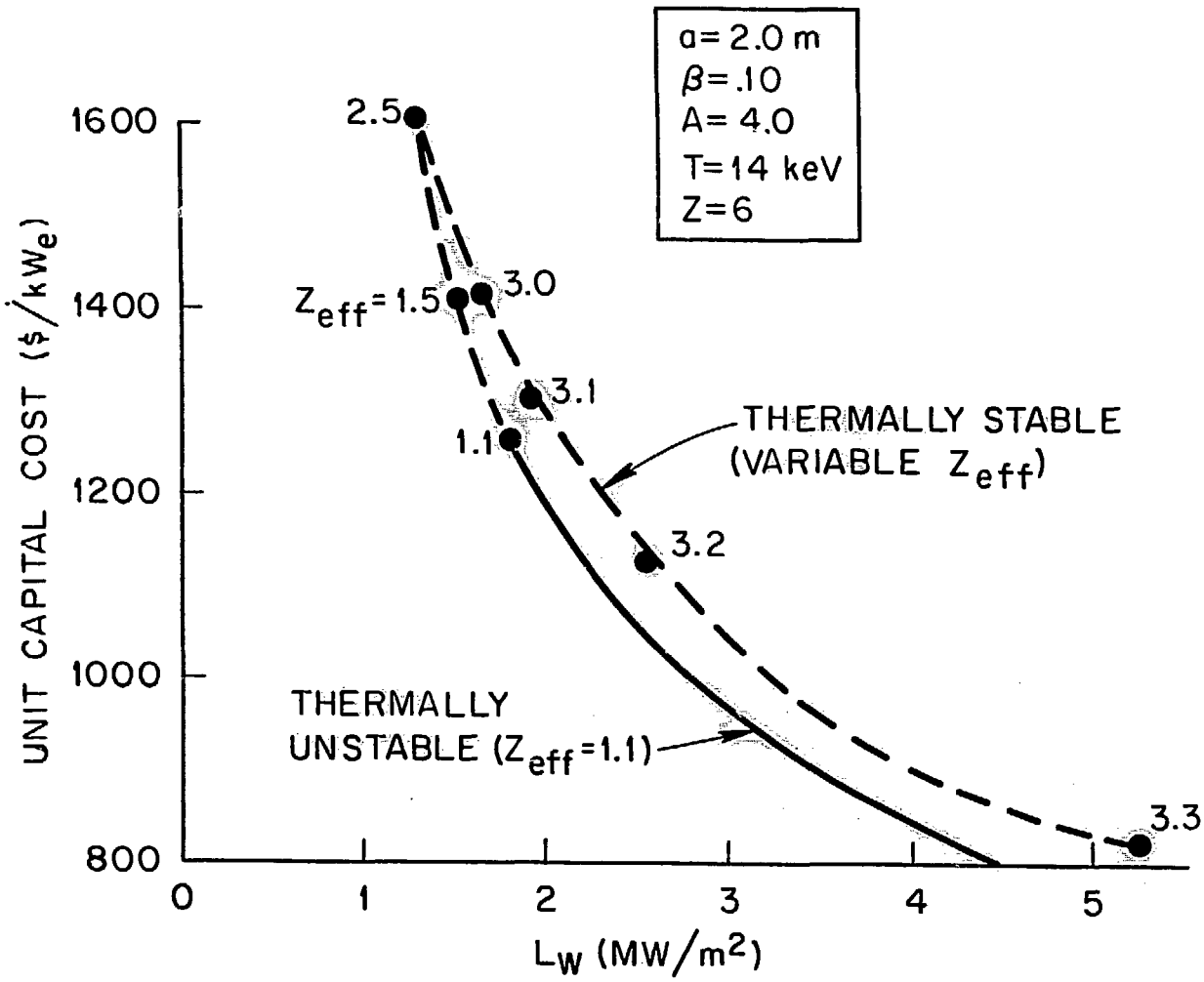

a= 2.0 m
β=.10
A= 4.0
T=14 keV
Z=6
1600
1400
1200
1000
800
UNIT CAPITAL COST ($/kWe)
2.5
Zeff=1.5
3.0
3.1
1.1
3.2
3.3
THERMALLY STABLE
(VARIABLE Zeff)
THERMALLY
UNSTABLE (Zeff=1.1)
0
1
2
3
4
5
LW (MW/m2)

FIGURE 4.

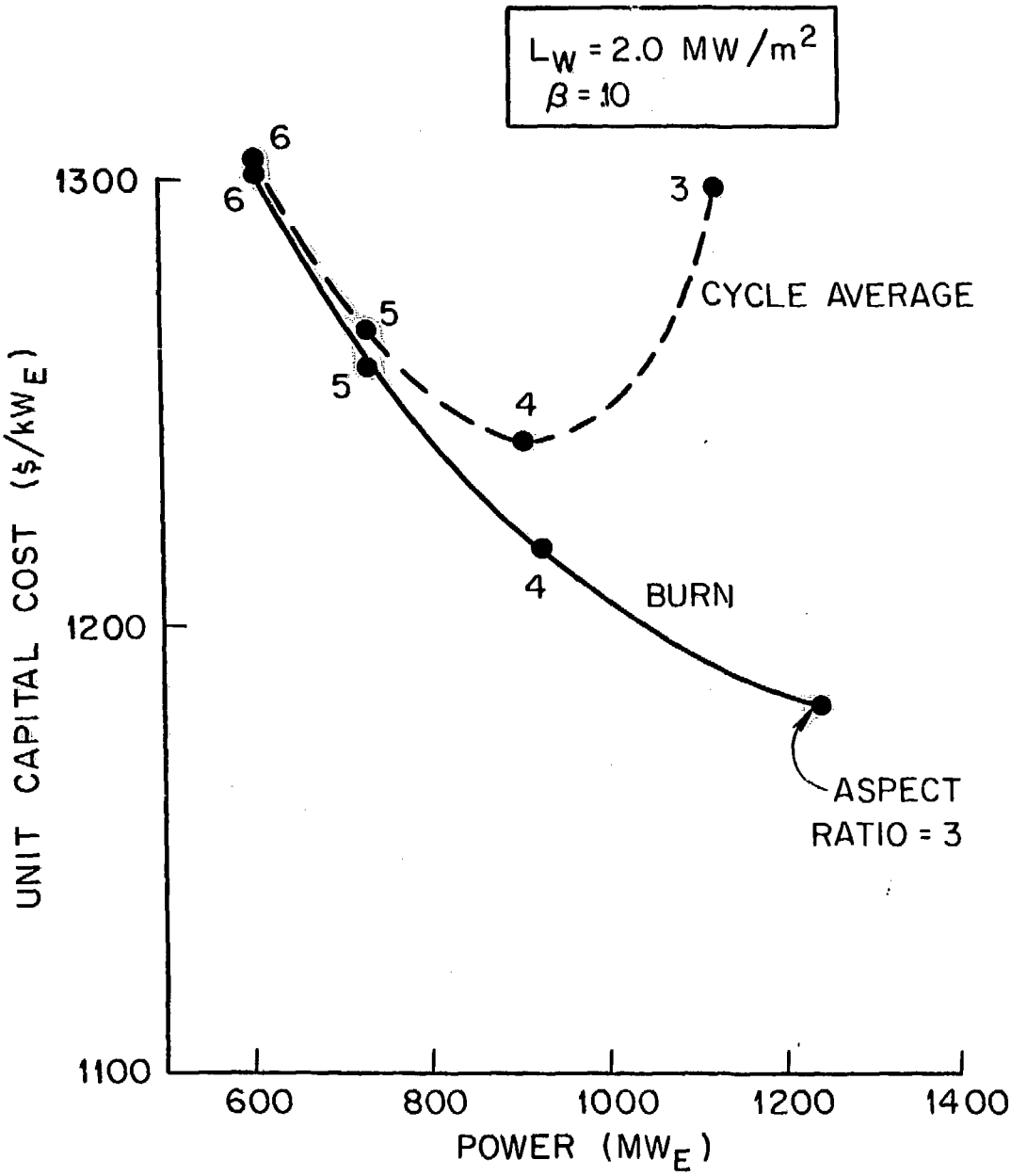

L_W = 2.0 MW/m^2
β = 10
1300
1200
1100
UNIT CAPITAL COST ($/kW$_E$)
600
800
1000
1200
1400
POWER (MW$_E$)
6
6
5
5
4
4
3
CYCLE AVERAGE
BURN
ASPECT
RATIO = 3

FIGURE 5.

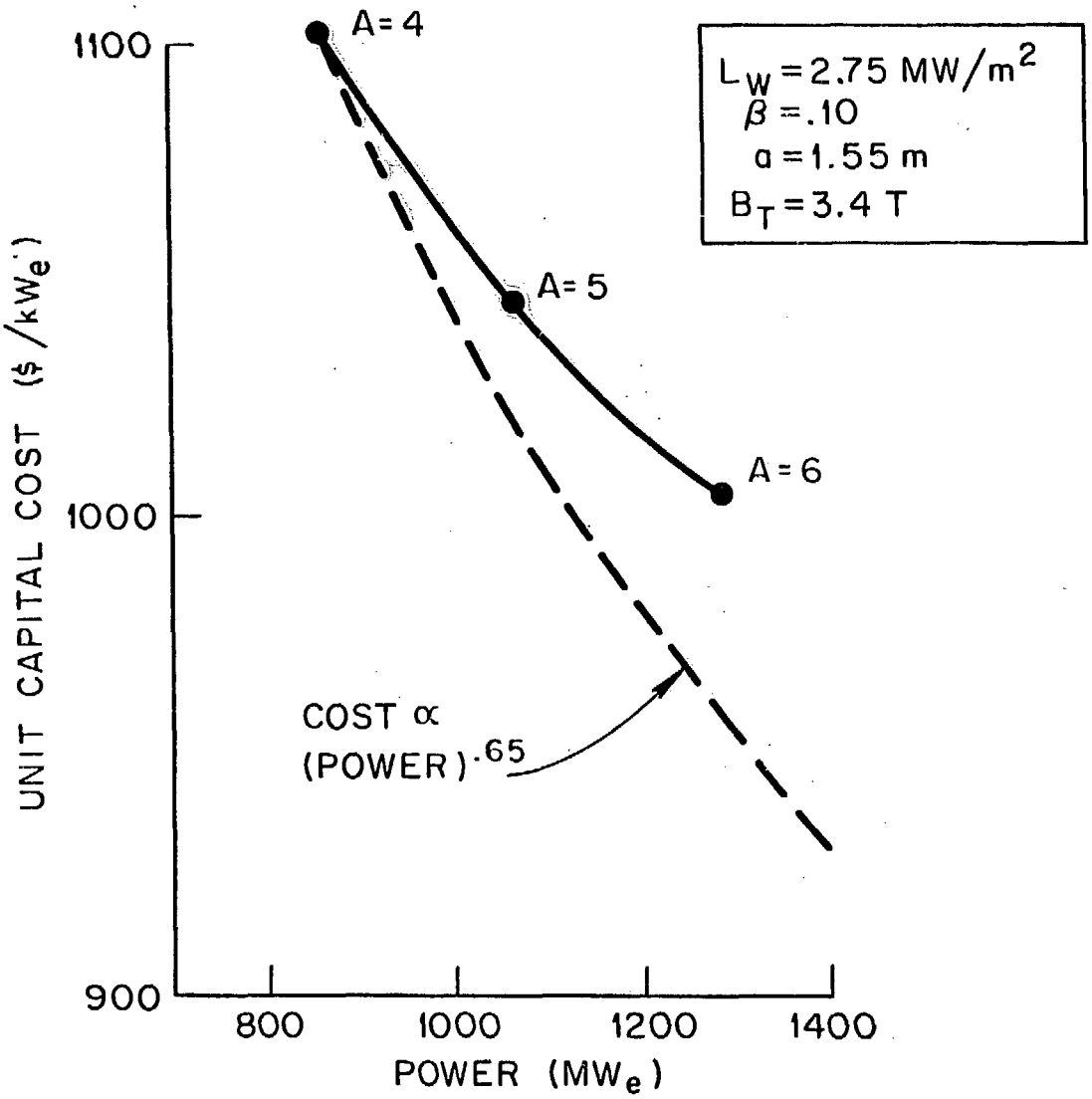

A=4
A=5
A=6
$L_W = 2.75\ MW/m^2$
$\beta = .10$
$a = 1.55\ m$
$B_T = 3.4\ T$
COST $\propto$ (POWER)$^{.65}$
UNIT CAPITAL COST ($/kW$_e$)
1100
1000
900
800
1000
1200
1400
POWER (MW_e)

FIGURE A-1.

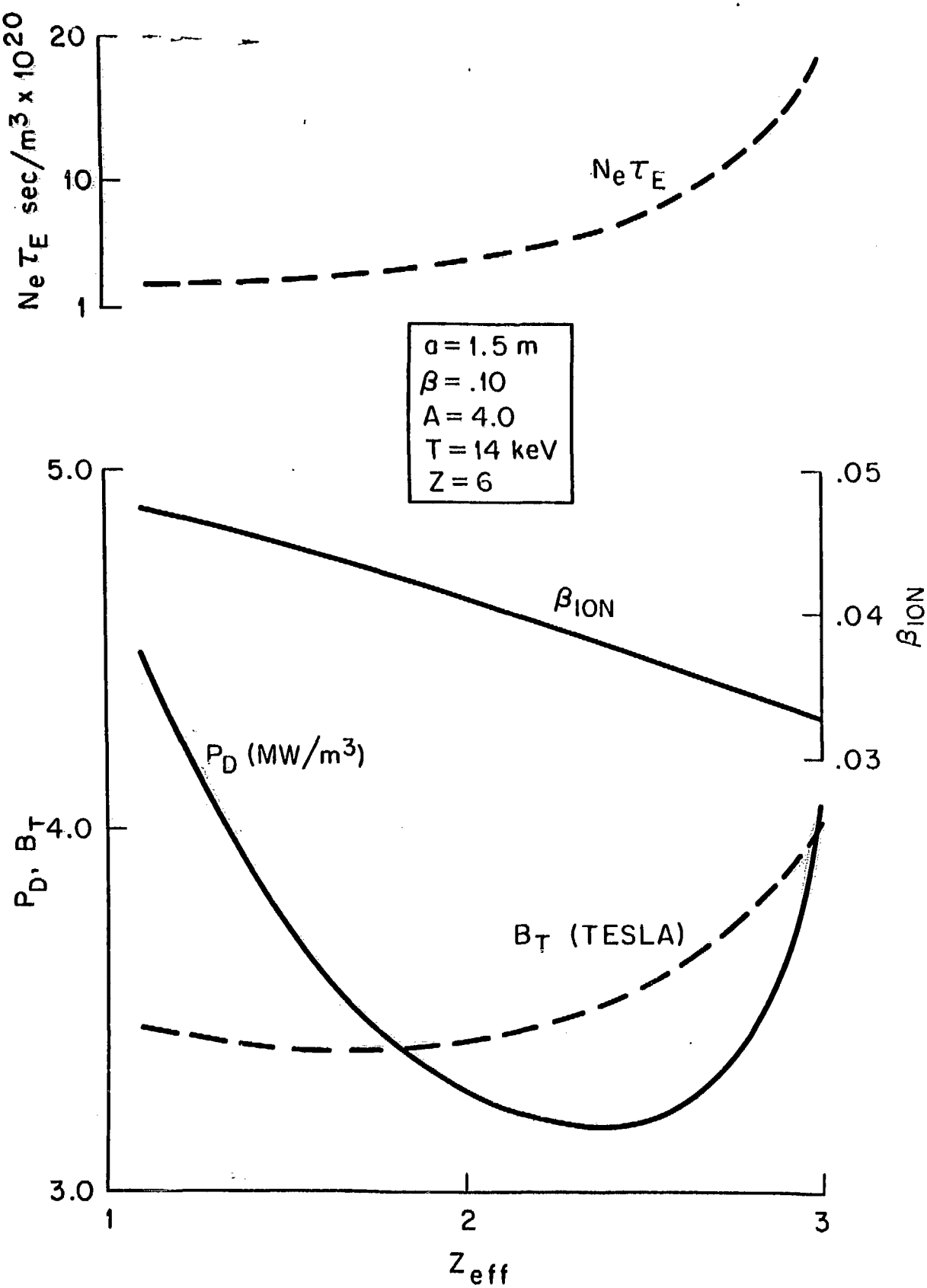

$N_e \tau_E$ sec/m^3 x 10^{20}
20
10
1
$N_e \tau_E$
a = 1.5 m
β = .10
A = 4.0
T = 14 keV
Z = 6
5.0
4.0
3.0
P_D, B_T
.05
.04
.03
β_{ION}
β_{ION}
P_D (MW/m^3)
B_T (TESLA)
1
2
3
Z_{eff}

FIGURE A-2.

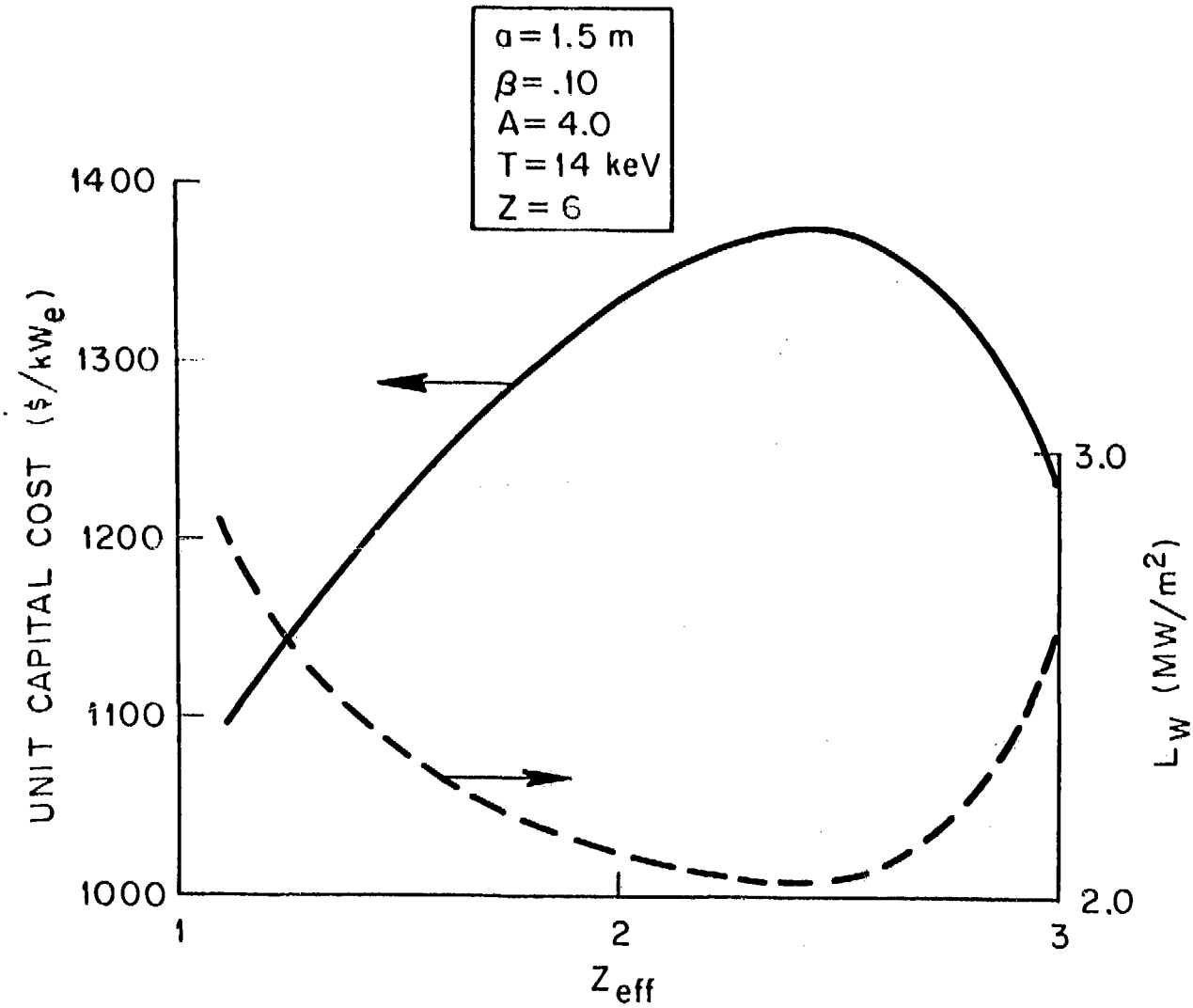
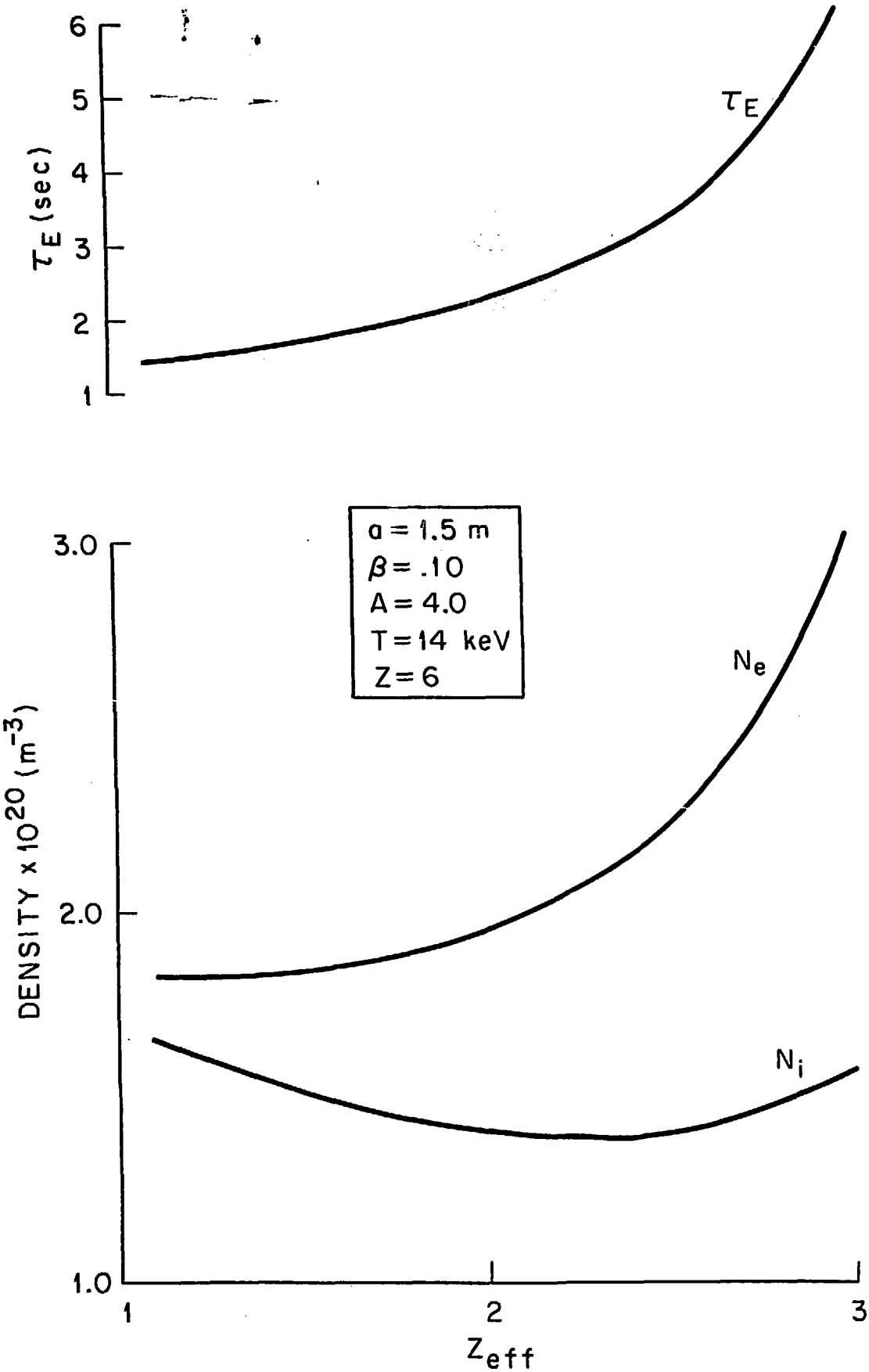

a = 1.5 m
β = .10
A = 4.0
T = 14 keV
Z = 6
1400
1300
1200
1100
1000
UNIT CAPITAL COST ($/kWe)
3.0
2.0
LW (MW/m2)
1
2
3
Zeff

FIGURE A-3.


6
5
4
3
2
1
τ_E (sec)
τ_E
a = 1.5 m
β = .10
A = 4.0
T = 14 keV
Z = 6
3.0
2.0
1.0
DENSITY x 10^{20} (m^{-3})
N_e
N_i
1
2
3
Z_{eff}