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1

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INTERNATIONAL THERMONUCLEAR ENGINEERING REACTOR: BIMODAL DEVICE AND DESIGN SENSITIVITIES TO ENERGY CONFINEMENT H-FACTORS

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CONTENTS

ABSTRACT

A major concern of present-day tokamak design is the uncertainty in the plasma energy confinement scaling. We present sensitivities of designs similar to the International Thermonuclear Engineering Reactor (ITER) to changes in the energy confinement H-factor (H) for cases designed for (1) ignition (the ITER physics phase), (2) long-pulse, current-driven operation (the ITER technology phase), and (3) achievement of both phases in a single device (bimodal). For cases that require ignition, the cost increases sharply for H-factors below 2. For technology-phase cases, the costs are much less sensitive to H-factor variations. For bimodal cases with $H \geq 1.8$, the ignition criteria dominate if the energy multiplication factor Q need only be 5 in the technology phase; if $Q \geq 10$ is required, the current drive criteria dominate. The bimodal cases are at most ≈10% more expensive than the more costly of the physics-only and technology-only cases. Thus, the present ITER scheme of replacing the blanket and shield of the device between phases may not be the most cost-effective way to accomplish the desired performance goals. Investigation of device sensitivity to the H-factor indicates that, as the H-factor decreases from 1.8 to 1.2 for a given device, the achievable Q drops from ≈10 to ≈5 and the divertor heat load increases by 50%.

1. INTRODUCTION

The International Thermonuclear Engineering Reactor[1] (ITER) has dual missions: (1) to demonstrate plasma ignition and (2) to demonstrate steady-state performance with a reasonable wall load (≈1 MW/m^2). A major uncertainty in the device design is the plasma energy confinement projection. The present ITER design calls for a two-phase approach that is intended to minimize the impact of this uncertainty. In the physics phase, a configuration with major radius R = 5.8 m and plasma current I_p = 22 MA is used to demonstrate ignition; in the technology phase, a configuration with R = 5.5 m and I_p = 18 MA is used to demonstrate steady-state operation. The higher plasma current in the physics phase improves the potential energy confinement, which is not as strong a concern in the technology phase. The configuration is changed by replacing the blanket/shield portion of the machine after the physics phase is completed.

We present the parameters of an ITER device that can perform both missions: a bimodal device that requires no retrofitting. This device is compared with cases that achieve the performance objectives of only the physics phase or the technology phase to clarify the relative advantages and disadvantages of the present ITER concept and of the bimodal approach.

We have evaluated these cases for a range of energy confinement H-factors H. For each case, we have determined the minimum device cost (size) for an assumed H-factor by allowing the device size, aspect ratio A, I_p, and other parameters to vary. We have also investigated the sensitivity of the performance capabilities (such as the energy multiplication factor Q) in a given device to changes in the H-factor. The results quantify the minimum H-factor required for adequate performance.

2. MODEL

The TETRA systems code[2] was used to model the devices considered. The physics modeling follows the latest ITER directives in ref. 3. Some of the physics constraints are given in Table 1. Quantities that are allowed to vary in the solution process are given in Table 2. The fusion power is limited to ≤1.25 GW to eliminate solutions with excessive heat transport problems and is calculated from

$$\int \langle \sigma v \rangle n_D n_T \, dV \ , \qquad (1)$$

Table 1. Constraints used in the study

	Physics phase	Technology phase
Power balance[a]	Yes	Yes
Energy gain Q	—	5, 10
Wall load Γ, MW/m^2	$\leq$2	1–2
Volt-second limit	Yes	No
Beta limit coefficient g	$\leq$2.5	$\leq$3.0
Fusion power, GW	$\leq$1.25	$\leq$1.25
Temperature profile factor	1.0	1.0
Density profile factor	0.5	0.5
Z_{eff}	2.16	2.16
Elongation (95% flux)	2.0	2.0
Traingularity (95% flux)	0.4	0.4
Safety factor q (95% flux)	3.0	3.0
Inner shield thickness,[b] m	0.75	0.85
TF coil configuration	Wedged	Wedged
Superconductor	Nb_3Sn	Nb_3Sn

[a]Power in $\geq$ power out; the energy confinement must be satisfied for Rebut-Lallia, Goldston, JAERI, and T-10 scaling, all with an H-factor $\leq$ the specified H-factor.
[b]The outer shield/blanket thickness is 1.6 m for all cases.

Table 2. Variables used in the study

Plasma variables	Engineering variables
Density[a]	TF coil thickness
Temperature[a]	TF coil case thickness
Major radius	OH coil thickness and bore
Aspect ratio	TF and OH coil copper fraction
Field on axis[a]	TF and OH coil conduit thickness
Beam injection angle	TF and OH coil current densities
	TF and OH coil cable sizes
	TF coil cable aspect ratio

[a]Can be different for the two phases of a single bimodal design.

where parabolic-type density and temperature profiles are used with the exponents given in Table 1.

For a specified H-factor, we require that the power balance

$$P_{\mathrm{alpha}} + P_{\mathrm{injection}} \geq P_{\mathrm{radiation}} + P_{\mathrm{transport\ loss}} \qquad (2)$$

be satisfied for the T-10, Goldston, JAERI, and Rebut-Lallia energy confinement scalings (explicit dependences for these scalings are given in ref. 3). The injection power $P_{\mathrm{injection}}$ consists of the current drive power and an optional heating power (not normally used); the current drive modeling assumes a combination of neutral beam injection and lower hybrid waves and follows the methodology described in ref. 4. The radiation power $P_{\mathrm{radiation}}$ includes bremsstrahlung and synchrotron radiation, with an 80% wall reflectivity.

The superconducting magnet analysis follows the methodology described in ref. 5 for a forced-flow, cable-in-conduit conductor. For the toroidal field (TF) coils and the ohmic heating (OH) solenoid, we limit the operating current to 6(% of the critical current, the temperature margin to ≥0.5 K, the dump time to ≥4 s, and the quench temperature rise (adiabatic) to ≤150 K. The superconductor is assumed to be Nb_3Sn, and the inlet helium temperature is taken to be 4.5 K.

Stress modeling follows the methodology described in ref. 6. The TF coils are in a wedged configuration, and the allowable stress in the cable conduit and outer case is 600 MPa. This is slightly lower than that used in actual design, but the additional margin incorporated in this way provides leeway for effects such as stress concentrations in corners, which are beyond the scope of systems code modeling. The stress used here is a Von Mises combination of the vertical component, the radial component from the centering load, and the toroidal component due to the wedging. The shear stress between the coils (from out-of-plane forces) is limited to 30 MPa.

All costs that we present are total direct costs; factors relating to construction services, plant engineering and construction, and project management are not included. The costing generally follows the methodology described in ref. 7, except that we use a more detailed costing (described in ref. 5) for the superconductor, which is a major cost driver.

Minimum-cost solutions are found by allowing the quantities listed in Table 2 to vary within the design constraints. Because the major radius R, the aspect ratio A, and the magnetic field are all allowed to vary, the entire plasma current–aspect ratio (I-A) space can be sampled in the search process. Although the dependence of the solutions on A, I_p, etc., can be shown explicitly, as is done in I–A space analysis (see, e.g., refs. 1 and 8), here we choose to concentrate on the overall sensitivity of cost and performance to energy confinement. We emphasize that, in addition to allowing I and A to vary, we let the peak field and the wall load vary, subject to the constraints discussed here and given in Table 1.

3. RESULTS

3.1 OVERALL DEVICE SENSITIVITY TO H-FACTOR

Figure 1 shows the parameters of a minimum-cost device vs H-factor for physics-only, technology-only, and bimodal cases with $Q \geq 5$. The bimodal case represents

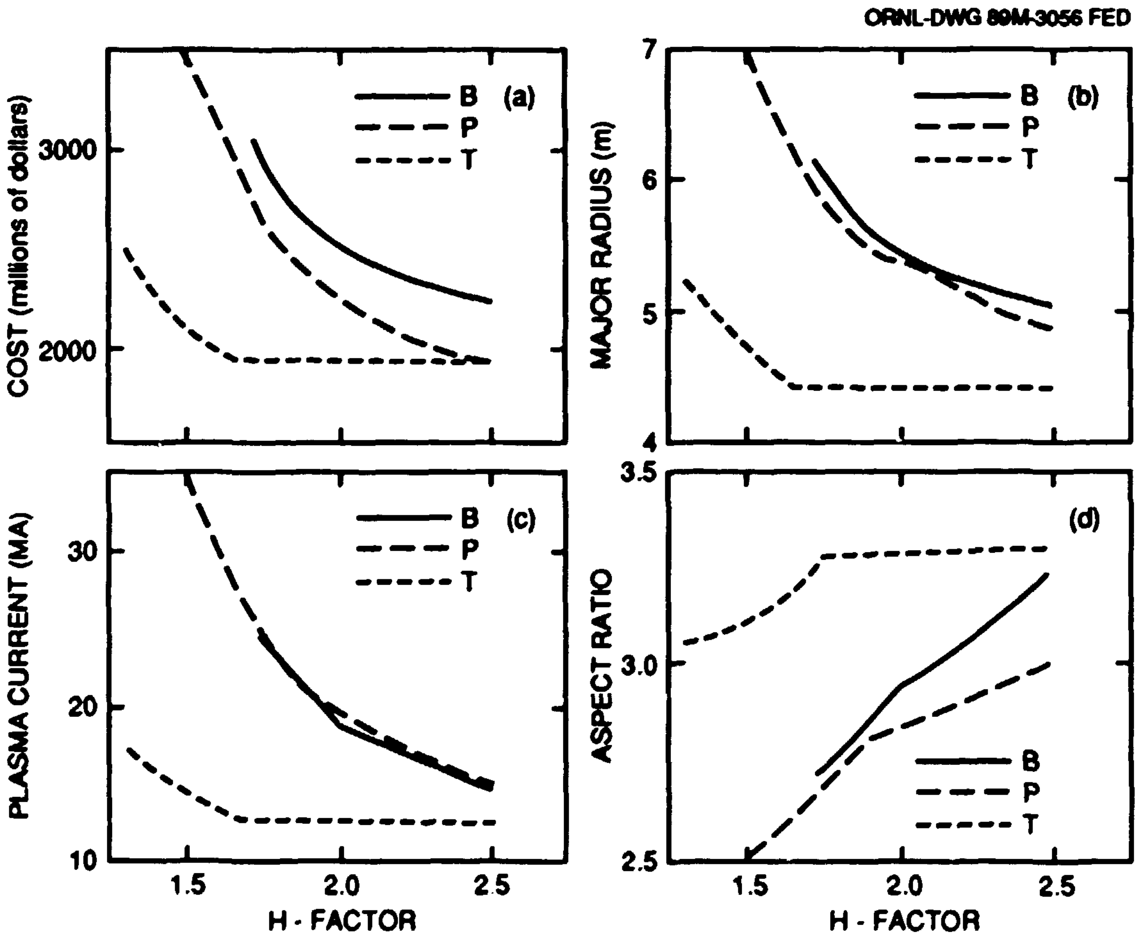

Fig. 1. (a) Minimum cost, (b) major radius, (c) plasma current, and (d) aspect ratio . H-factor for technology-phase, physics-phase, and bimodal devices with a required $Q \geq 5$.

a single device that satisfies the constraints of both the physics phase and the technology phase with a 0.85-m-thick inboard blanket/shield. The minimum-cost technology-only case is insensitive to variations in the H-factor for $H \geq 1.5$, whereas the minimum-cost physics-only case is quite sensitive to such variations for $H \leq 2$. The physics constraints drive the bimodal device for $H \leq 2.5$. For the technology-only case, increasing the H-factor beyond 1.75 offers no further cost reduction because the constraints on beta limit, minimum wall load, and magnets become the primary limitations. An important feature to note here with regard to the following analysis is that the device parameters (size, field, and current) are adjusted to minimize their impact on varying H-factor.

When the model used here is applied to the $R = 5.8$-m baseline physics-only ITER, we find that H-factors of 1.8 for the JAERI scaling, 1.9 for the Goldston scaling, 1.8 for the T-10 scaling, and 0.9 for the Rebut-Lallia scaling are needed for ignition. Setting $H \approx 1.9$, we find that the minimum-cost bimodal device has $R = 5.5$ m, $I_p = 20$ MA, and $A = 2.8$. The requirement of $Q \geq 5$ for the bimodal case is easily met, as shown in Fig. 1, where Q goes from 12 to 8 as the H-factor goes from 1.75 to 2.5. In the results presented here, the power balances for physics-only performance are generally limited by the JAERI, Goldston, and T-10 scalings; those for the technology-only cases are primarily limited by the JAERI scaling.

An ITER device that requires ignition for some prescribed H-factor during the physics phase and $Q \geq 5$ will cost at least as much as the minimum-cost physics-only designs shown in Fig. 1, which do not include the cost of shutdown and retrofitting of the present ITER concept. The bimodal case shown in Fig. 1 accomplishes both missions with no retrofitting for about $100 million to $200 million (≈10% of the direct cost) more than the minimum-cost physics-only case. Most of the cost differential between the physics-only and the bimodal cases in Fig. 1 lies in the larger inboard blanket and higher injection power for the bimodal case; cost penalties in both areas would be incurred if a retrofitting scheme were employed. The retrofitting concept incurs additional cost penalties associated with down time for the blanket replacement, design complications in the extra blanket/shield components (extra piping, etc.), and added complexity in remote maintenance systems; these are beyond the scope of this model.

Figure 2 shows minimum-cost cases in which Q is required to be ≥10 in the technology-only and bimodal cases. The bimodal case is dominated by the requirements of the physics phase for $H \leq 1.7$ but by the requirements of the technology

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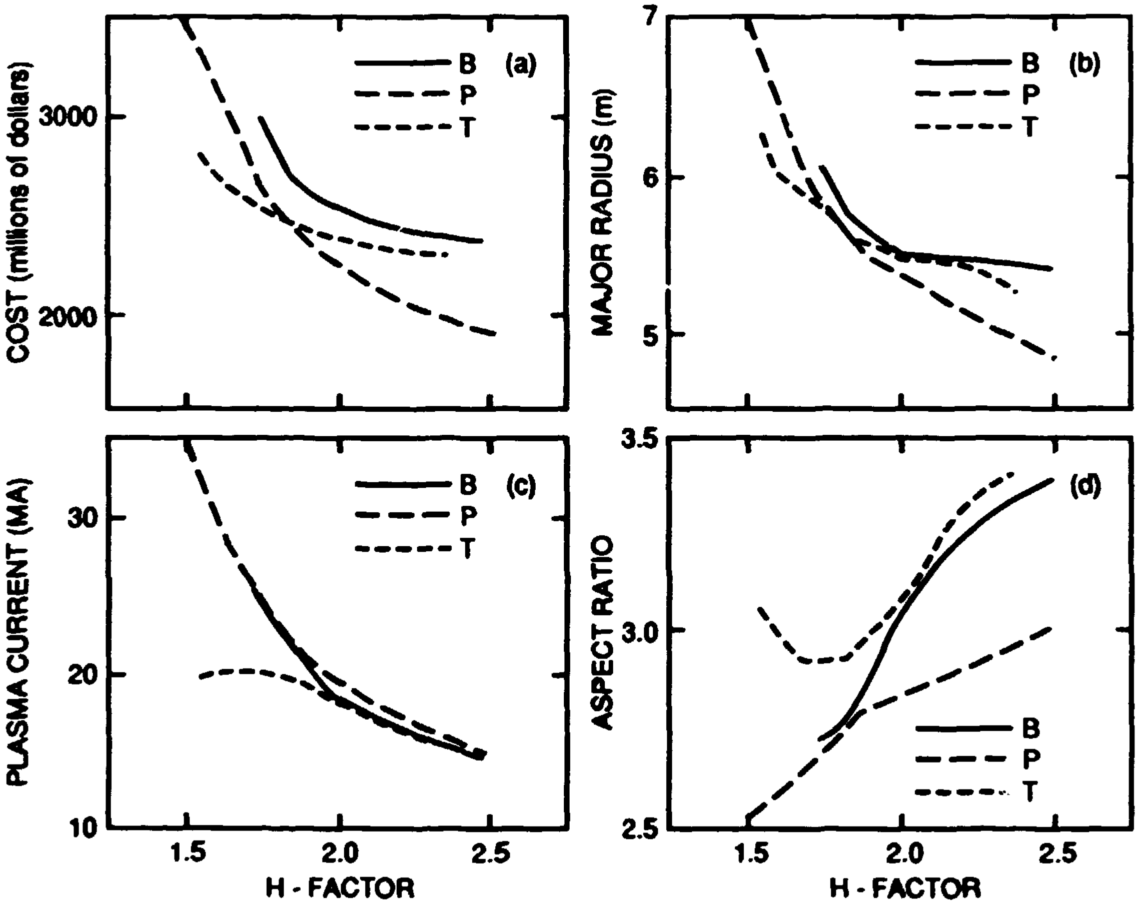

Fig. 2. (a) Minimum cost, (b) major radius, (c) plasma current, and (d) aspect ratio vs H-factor for technology-phase, physics-phase, and bimodal devices with a required $Q \geq 10$.

phase for $H > 1.7$. For example, the aspect ratio of the bimodal case is closer to that of the physics-only case for $H < 1.8$ ($A \approx 2.5$–2.8) and closer to that of the technology-only case for $H \geq 1.8$ ($A \approx 2.8$–3.5). Again, the actual Q in the bimodal case exceeds the required value; as H goes from 1.7 to 2, Q goes from 10 to 13. For $H \geq 1.8$ in Fig. 2, the bimodal case is only \$100 million to \$200 million more expensive than the technology-only case. For $H < 1.8$, there is little difference in the cost of the bimodal cases in Figs. 1 and 2. Thus, even when higher Q is required, the costs associated with the bimodal case are similar to those of a retrofitting approach.

As noted earlier, in these minimum-cost studies I_p, A, the wall load, and the peak TF coil field are allowed to vary, in contrast to the conventional I–A approach[1,8] in which peak field and wall load are held constant while I and A are varied. We find that minimum-cost solutions occur over a range of wall loads and peak fields. For physics-only designs, the wall load varies from 0.75 to 1.5 MW/m^2 and the peak field varies from 10.5 to 11 T at the minimum-cost points. For technology-only designs and for the bimodal case, the wall load varies from 1 to 1.5 MW/m^2 and the peak field varies from 10.5 to 12.5 T at the minimum-cost points.

3.2 SENSITIVITY OF FIXED-DEVICE PERFORMANCE TO H-FACTOR

We have examined the sensitivity to the H-factor of the technology-phase performance of a device with fixed parameters; the results are used to determine the sensitivity of Q to uncertainties in the energy confinement scaling. In these studies, we used the engineering variables listed in Table 2 and the major radius and aspect ratio determined from the calculation of the minimum-cost point with $H = 1.8$, which yielded $R = 5.57$ m, $A = 2.9$, and $I_p = 20$ MA. Plasma temperature and density, magnetic field (and hence plasma current), and injection power are allowed to vary so that Q can be maximized, subject to the engineering and physics constraints.

Figure 3 shows the maximum Q, injection power, fusion power, neutron wall load, peak divertor heat load, and plasma density and temperature vs H for the technology-only design determined with $H = 1.8$. No improvement in the maximum Q is obtained with $H > 1.85$ because the constraints on beta limit, wall load, and magnets dominate. As H decreases from 1.8, more power input to the plasma is required to maintain the plasma power balance, so the injection power and fusion power increase; these increases are accommodated by a decrease in plasma temperature and a slight increase in density. The overall effect on Q is a factor of 2 reduction as H decreases from 1.8 to 1.25. The neutron wall load and the peak divertor heat load also increase with this increase in power (calculation of the peak divertor heat load is discussed in the appendix). Part of the lower H-factor regime indicated here may be ruled out by excessive divertor heat loads. Also, beta is below the Troyon limit at the lower H-factors.

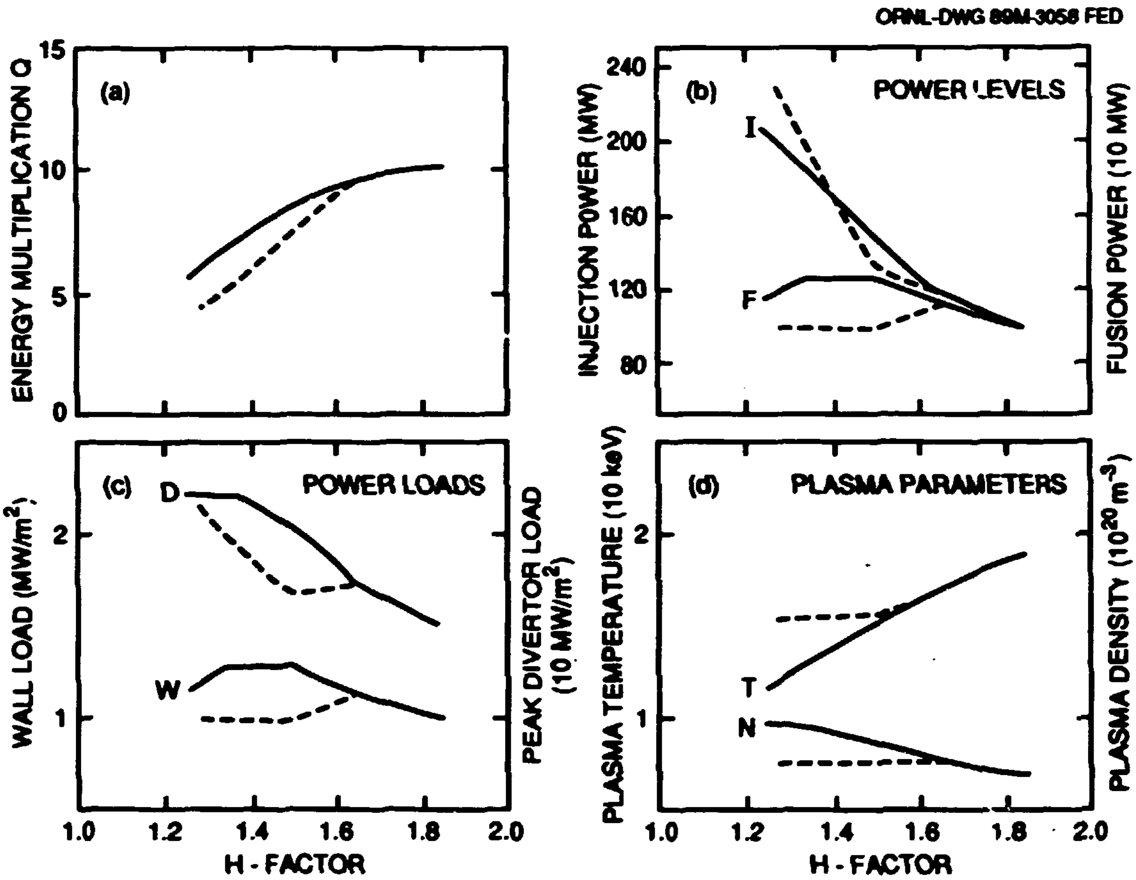

Fig. 3. Effect of H-factor variation on the parameters of a minimum-cost technology-phase device calculated for an H-factor of 1.8. (a) Maximum Q. (b) Injection power and fusion power. (c) Neutral wall load and divertor heat load. (d) Plasma temperature and density. The dashed lines indicate the parameters when the beam injection angle is fixed and additional heating power is supplied.

The beam injection angle was allowed to vary for the case illustrated in Fig. 3. For $H < 1.65$, the tangency radius drops below the major radius R, indicating that more perpendicular beam injection with a shorter beam penetration path length is required. At $H = 1.25$, the beam tangency radius is at $(R - a)/3.5$, where a is the plasma minor radius. If the beam injection angle and the beam energy are held constant, the temperature must remain high and the density low to ensure beam penetration to the center of the plasma. This can be done if additional heating power (which need not contribute to current drive) is included for $H < 1.65$. The dashed lines in Fig. 3 indicate the results when this heating power is added. The maximum Q is lower when the additional power is used. However, if the neutral beam energy and beam injection angle are fixed, then adding some heating power may be the only way to maintain the power balance and current drive for low H-factors. The wall and divertor heat loads are slightly lower when additional power is used because of the lower fusion power levels.

Figure 4 shows the maximum Q, injection power, fusion power, neutron wall load, peak divertor heat load, and plasma density and temperature vs H for a bimodal case with $R = 5.93$ m and $A = 2.8$. Here we pick the minimum cost bimodal device at $H = 1.8$ and freeze the radial build. The aspect ratio for this case is slightly lower than that for the technology-phase device (see Fig. 2). The effect on Q of variations in H is similar to that for the case in Fig. 3; the maximum

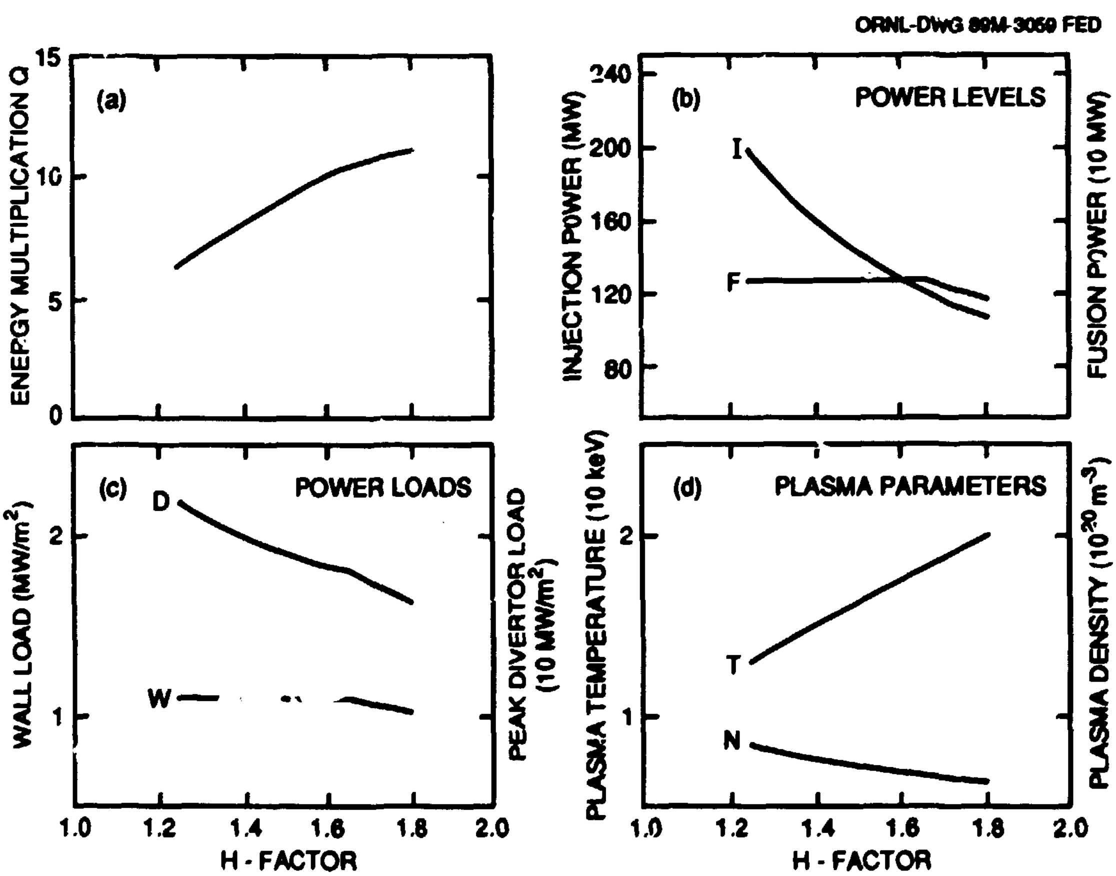

Fig. 4. Effect of H-factor variation on the parameters of a minimum-cost bimodal device calculated for an H-factor of 1.8. (a) Maximum Q. (b) Injection power and fusion power. (c) Neutral wall load and divertor heat load. (d) Plasma temperature and density.

Q at $H = 1.8$ is slightly higher (11 vs 10) for this case. The beam tangency radius does not change as much in this case; it begins to drop below R at $H = 1.6$ and is at $(R - a)/6.3$ for $H = 1.25$.

The minimum-cost point for the technology-only case at $H = 2.0$ ($R = 5.4$ m, $A = 3.0$, $I_p = 19$ MA) was also evaluated to determine its sensitivity to changes in H. This case is slightly smaller than those at $H = 1.8$ (see Fig. 2). The results were similar to those in Figs. 3 and 4.

4. SUMMARY

Energy confinement considerations play a key role in the selection of the design point for ITER-type machines. We have considered the impact of energy confinement scalings on devices designed to meet the requirements of the physics phase, devices designed to meet the requirements of the technology phase, and bimodal devices designed to meet both sets of requirements without retrofitting. The energy confinement is characterized in terms of the leading coefficients used in energy confinement scaling expressions. In general, energy confinement is the dominant influence on devices that are required to ignite with $H \leq 2$ and has less effect on devices designed to meet only the technology-phase criteria. For bimodal designs with $H \geq 1.8$, if the energy multiplication factor Q need only be ≥ 5 in the technology phase, then the physics-phase guidelines dominate the design; for $Q \geq 10$, the technology-phase guidelines dominate. In all cases examined for a fixed H-factor, the bimodal devices are at most $100 million to $200 million more expensive than a device that would accomplish the more costly set of single-phase requirements (either technology or physics phase, depending on the required Q). This cost difference is expected to be small compared to the cost and challenges of retrofitting a device to accomplish both missions, as called for in the present ITER concept.

For a given design, uncertainties in the energy confinement play a role in the expected performance. We have examined the sensitivity of the technology-phase Q to uncertainties in the H-factor. For a device designed to achieve $Q = 10$ with $H = 1.8$, the maximum possible Q decreases to 5 if the H-factor is in fact only 1.2. This decrease is accompanied by an increase of ~40 to 50% in the divertor heat load because of the additional heating power required. The ability of the device to handle this increase in the divertor heat load determines its tolerance to confinement shortfalls of about 40% in the H-factor.

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Appendix

DIVERTOR HEAT LOAD CALCULATION

The heat load on the outer divertor plate (i.e., that part of the divertor which is contacted by the outer flux surfaces) is calculated from

$$P_{\rm div} = C_p P_{\rm ch} f_o f_s / A_{\rm div} \ ,$$

where $C_p = 3$ is the ratio of the peak heat load to the average heat load, $P_{\rm ch} = P_\alpha + P_{\rm injection}$ is the charged particle power, $f_o = 0.75$ is the fraction of the power deposited on the outer divertor, $f_s = 0.75$ is the fraction of the charged particle power that strikes the divertor, and $A_{\rm div} = 4Rt_{so}/\sin\theta$ is the outer divertor surface area (of both the top and bottom divertors), with $t_{so} = 1.0$ m the scrape-off thickness in the divertor area and θ the average angle of incidence of the field lines on the divertor. The rest of the power is assumed to be lost via radiation and neutral particle interactions.