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A Systems Analysis of the ARIES Tokamak Reactors†

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The multi-institutional ARIES study has completed a series of cost-of-electricity optimized conceptual designs of commercial tokamak fusion reactors that vary the assumed advances in technology and physics. A comparison of these designs indicates the cost benefit of various design options. A parametric systems analysis suggests a possible means to obtain a marginally competitive fusion reactor.

1. INTRODUCTION

The Advanced Reactor Innovation and Evaluation Study (ARIES)[1] is a multi-year, multi-institutional study, which is just now coming to a close, of three tokamak-reactor visions emphasizing economic, safety, and environmental features. The first of these reactor vision studied is the D-T fueled ARIES-I[2] reactor design, which uses the conventional physics (β=1.9 %) of the first stability regime (FSR) and advanced superconducting technology (21 T at the TF coil). The ARIES-I design optimizes the cost-of-electricity, COE, at high plasma aspect ratio (A = 4.5), where the current-drive power and cost are minimized. The D-^{3}He fueled ARIES-III design[3] is the second of the reactor vision studied. The ARIES-III design requires significant advances both in engineering and physics. The technological advances invoked for ARIES-III include: high efficiency (η_{CD}=0.68), energetic (3-6 MeV) neutral beams for current drive and advanced superconducting coils (40 MA/m^2 in TF coils). Economics dictates that ARIES-III operate in the high-beta (β=23.9 %) second stability regime (SSR) to open a severely restricted power-balance operating space by reducing magnetic field ($B_{\phi 0}$=7.6 T) and plasma current (I_ϕ=30 MA), respectively. The third reactor vision studied is represented by the DT-burning ARIES-II and -IV designs[4], which are in the final stage of completion. Both designs are based on advanced physics (SSR) and nearer-term technology (16 T peak field and 30 MA/m^2 for the TF coils). These two designs have similar plasmas parameters, but different blanket and shield designs: ARIES-II uses a liquid-Li-cooled, V-alloy blanket; and ARIES-IV uses a He-cooled, SiC blanket (similar to ARIES-I). The ARIES-II and -IV designs exploit the SSR more for reduced total plasma current (I_p < 7 MA) and a bootstrap-current fraction near unity, rather than for a high beta (β=3.4 %).

2. MODEL

All of the ARIES designs were parametrically analyzed with the ARIES systems code (ASC)[4], which examines different fuel mixes, blankets, and beta limits. The ASC has necessarily evolved during the course of the ARIES project to account for advances in physics and technology. All of the designs reported herein have been (re)analysed with the latest version of ASC.

The updated models used in the ASC are described in Ref. 4, with essential features and notation summarized below. The axisymmetric plasma is characterized by the major toroidal radius, R_T; equatorial-plane minor radius, a; vertical elongation, κ; and triangularity, δ. The plasma toroidal beta for the FSR is constrained by a Troyon-type relation: $\beta \equiv 2\mu_0 < p > / B_{\phi 0}^2 = C_T I_\phi / a B_{\phi 0}$; where $< p >$ is the volume averaged plasma pressure, $B_{\phi 0}$ is the vacuum toroidal magnetic field on axis ($R \simeq R_T$), and C_T is determined by ballooning stability. For the SSR, the toroidal beta has been reformulated to see more clearly the effects of stability as $\beta \equiv \epsilon(\epsilon\beta_\theta)S^2/q_*^2$; where $\epsilon \equiv A^{-1} = a/R_T$, β_θ is the poloidal beta, $S^2 = (1+\kappa^2)/2$, and q_* is a circularized safety factor. An equilibrium limit constrains $\epsilon\beta_\theta \leq 1.85$, and kink stability constrains $q_*^2 > 16$.

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Central to the ASC is a zero-dimensional, steady-state plasma-power-balance model[5] that includes ion and electron energy balance; protium, deuterium, tritium, helium-3 and helium-4 (alpha) particle continuity; a specified impurity fraction; charge balance; a plasma beta constraint; and a magnetic equilibrium constraint. The zero-dimensional equations are derived from a radial average over specified plasma profiles that preserve the peak-to-average values of pressure and density determined by detailed equilibrium and current-drive calculations. The fractional fusion power deposited in the ions is calculated from time integrals of the fusion-product slowing down rates. The parameters input into this model include the ion temperature, T_i; the toroidal plasma current, I_ϕ; the ratio of particle-to-energy confinement time, τ_p/τ_E; the ratio of ion-to-electron energy confinement time, τ_{Ei}/τ_{Ee}; and particle refueling fractions, $\phi_{^3He} + \phi_T + \phi_D = 1$. The computed parameters include ion density fractions; the electron temperature, T_e; the Lawson parameter, $n_i\tau_E$; and the suprathermal beta. The required τ_E is then expressed as a ratio $H = \tau_E/\tau_{ITER-89P}$; where $\tau_{ITER-89P}$ is the confinement time predicted by the ITER-89P scaling[6]

All of the ARIES designs require some fraction, f_{BC}, of the plasma current be driven internally by the pressure-gradient-driven bootstrap effect. In the FSR, $f_{BC} \propto \epsilon^{1/2}\beta_\theta$. In the SSR, $\epsilon\beta_\theta$ is sufficiently large that f_{BC} can be unity in the FSR scaling. Even if the global bootstrap current-drive fraction is unity, some externally driven current is required to match the (externally and internally) driven radial current-density profile with the equilibrium current-density profile; an on-axis seed current, a current to cancel the bootstrap overdrive at intermediate radii, and an edge current must be driven externally. For the high-beta ARIES-III, this mismatch between current-density profiles is large, so that the externally driven current is constrained to $|1 - f_{BC}| \geq 0.25$. The high temperature required to maximize the D-^{3}He fusion power requires neutral beam injection (NBI) for current drive, whereas the lower temperature ARIES-I, -II, and -IV designs use a combination of ICRF and LHRF for current drive. The ARIES-II and -IV designs have a lower beta ($\beta = 3.4\%$) than ARIES-III to minimize the externally driven current. A temperature dependent model for each of the three components of the externally driven current is used for the ARIES-II and -IV designs.

Each of the ARIES designs has a separate model for the blanket, shield, and coils. The structural material in the blanket and shield of ARIES-I and -IV is a SiC composite with He coolant. The breeding materials are Li_2ZrO_3 and Li_2O, respectively. A thicker blanket and shield is used for ARIES-I than ARIES-IV (1.39 versus 1.31 m inboard and 1.79 versus 1.74 m outboard, respectively). The ARIES-III design requires only a shield that is 0.65 and 0.80 m thick inboard and outboard, respectively. The ARIES-III shield material is HT-9, and an organic coolant is used in the reduced neutron environment to obtain a high thermal efficiency, $\eta_{TH} = 0.44$. The ARIES-IV design use V_5Cr_5Ti as structural material with a liquid-metal coolant (Li). The blanket and shield are 1.06 and 1.56 m thick inboard and outboard, respectively. A gap of 0.15 m is provided between the shield and the TF coils on the outboard side in ARIES-I. In ARIES-III, this gap is 0.40 m to provide shielding for beam-line penetrations. In ARIES-II and -IV, the gap is determined by the requirement that blanket sections be removed horizontaly between TF coils and is 1.36 and 1.44 m, respectively. Scrapeoff thicknesses of 0.10 and 0.05 m are used for ARIES-I and -III and for ARIES-II and -IV, respectively. For ARIES-III, the outboard scrapeoff thickness is increased to 0.90 m to decrease the neutron wall loading to 0.1 MW/m^2. Constant-tension TF coils are used for all designs except ARIES-III, which used a TF coil that fits snuggly to the shield (allowing for required gaps) to minimze the TF-coil mass.

3. RESULTS

Reactor parameters for all four ARIES designs are given in Table I, and elevation views of the reactors are shown in Fig. 1. The ARIES-I COE reported in Table I is 45% larger than reported in Ref. 2, because of model refinements (50%), inflation (15%), and safety credits (−20%). Similarly, the ARIES-III COE reported in Table I is 3% larger than reported in Ref. 3 because of model refinements (−2%) and inflation (5%). To separate the cost benefits of the physics from the engineering, a fifth design, ARIES-Ia, is considered that is based on the ARIES-I design, but substitutes the ARIES-IV blanket and shield. The ARIES-Ia design requires a larger plasma than the ARIES-I design, because the blanket energy multiplication is 9% lower. The larger ARIES-Ia design yields a lower COE than the ARIES-I design, because the unit cost of the blanket and shield is lower. As seen from the breakdown of the Reactor Equipment Cost (Account 22.1) in Fig. 2, only the blanket is cheaper in ARIES-Ia than ARIES-I. The ARIES-IV (ARIES-Ia) blanket and shield design has been optimized to minimize blanket replacement that results in an additional cost savings shown in the breakdown of the COE in Fig. 3. The low fusion power density of D-^{3}He relative to D-T makes ARIES-III the largest of the ARIES designs. The reason why the COE

TABLE I Comparison of Reactor Parameters for ARIES-I, -Ia, -II, -III, and -IV.

Parameter	ARIES-I	ARIES-Ia	ARIES-II	ARIES-III	ARIES-IV
Stability regime	FSR	FSR	SSR	SSR	SSR
Direct conversion	No	No	No	Yes	No
Fuel mix, ϕ_D/ϕ_T	0.5/0.5	0.5/0.5	0.5/0.5	0.5/0.0	0.5/0.5
Major toroidal radius, R_T(m)	6.75	7.51	5.60	7.5	6.12
Minor radius, a(m)	1.50	1.67	1.40	2.50	1.53
Plasma elongation, κ	1.80	1.80	2.03	1.84	2.03
Plasma triangularity, δ	0.70	0.70	0.67	0.81	0.67
Plasma aspect ratio, $A = R_T/a$	4.5	4.5	4.0	3.0	4.0
Edge safety factor, q	4.50	4.50	12.2	6.85	12.2
Peak-to-average ratio:					
density, n_0/n	1.30	1.30	1.12	1.06	1.12
temperature, T_0/T	1.90	1.90	2.65	1.75	2.65
Troyon coefficient, C_T(Tm/MA)	0.032	0.032	0.059	0.151	0.059
Plasma beta, β	0.019	0.019	0.034	0.24	0.034
Plasma poloidal beta, β_θ	2.80	2.80	5.40	5.41	5.40
Stability parameter, $\epsilon\beta_\theta$	0.62	0.62	1.35	1.80	1.35
Ion temperature, T_i(keV)	20	20	10	55	10
Electron temperature, T_e(keV)	18.9	19.0	10.3	53.5	10.3
Ion density, $n_i(10^{20}/\mathrm{m}^3)$	1.29	1.14	2.17	2.03	1.99
Electron density, $n_e(10^{20}/\mathrm{m}^3)$	1.56	1.38	2.53	3.20	2.32
Particle-to-energy confinement time ratio, τ_p/τ_E	4	4	10	2	9
Ion-to-electron energy confinement time ratio, τ_{Ei}/τ_{Ee}	1	1	1	1	1
Lawson parameter, $n_i\tau_E(10^{20}\mathrm{s/m}^3)$	4.1	4.0	2.7	24.3	2.9
ITER-89P confinement-time multiplier[6], H	3.7	3.6	3.0	8.0	3.1
Plasma gain, $Q_p = P_F/P_{CD}$	19.5	20.5	26.1	16.5	27.4
On-axis toroidal field, $B_{\phi 0}$(T)	10.7	10.1	8.01	7.39	7.66
Field at TF coil, $B_{\phi c}$(T)	20.1	18.4	16.0	13.6	15.9
Radiation fraction, f_{RAD}	0.48	0.47	0.18	0.68	0.23
Plasma current, I_ϕ(MA)	9.7	10.1	6.5	29.1	6.8
Bootstrap-current fraction, f_{BC}	0.68	0.68	0.89	0.94[a]	0.89
Current-drive efficiency, γ(mA/W)	31	32	9.6	45	9.6
Current-drive power to plasma, P_{CD}(MW)	99	102	75	160	78
Fusion-power density, $p_F(\mathrm{MW/m}^3)$	3.94	3.11	4.88	1.81	4.11
Neutron wall loading ($\mathrm{MW/m}^2$):					
14.1-MeV	2.2	2.1	3.1	0.06	2.87
2.5-MeV	~0	~0	~0	0.02	~0
Blanket energy multiplication, M_N	1.30	1.18	1.38	2.21	1.18
Thermal conversion efficiency, η_{TH}	0.49	0.49	0.46	0.44	0.49
Thermal power, P_{TH}(GWth)	2.55	2.56	2.63	3.96	2.59
Gross electrical power, P_{ET}(GWe)	1.25	1.25	1.21	1.30	1.27
Net electrical power, P_E(GWe)	1.0	1.0	1.0	1.0	1.0
Recirculating power fraction, $1/Q_E$	0.20	0.20	0.17	0.23	0.21
Mass power density, MPD(kWe/tonne)	89.3	75.4	97.1	89.4	118.5
Level of safety assurance[7], LSA	2	2	3	2	2
Reactor equipment cost, (B$)[b]	1.35	1.32	0.88	1.14	0.98
Total direct cost, TDC(B$)[b]	2.47	2.45	2.08	2.22	2.07
Total cost (B$)[b]	4.76	4.72	4.08	4.28	4.00
Cost of electricity, COE(mill/kWeh)[b,c]	94(107)	84(97)	73(80)	89(101)	7[illegible](85)

[a] The plasma current driven externally is constrained to be greater than 25% of the plasma current.

[b] All costs are reported in 1992 $.

[c] The COE without safety cost credits ($LSA = 4$) is also reported in parenthesis.

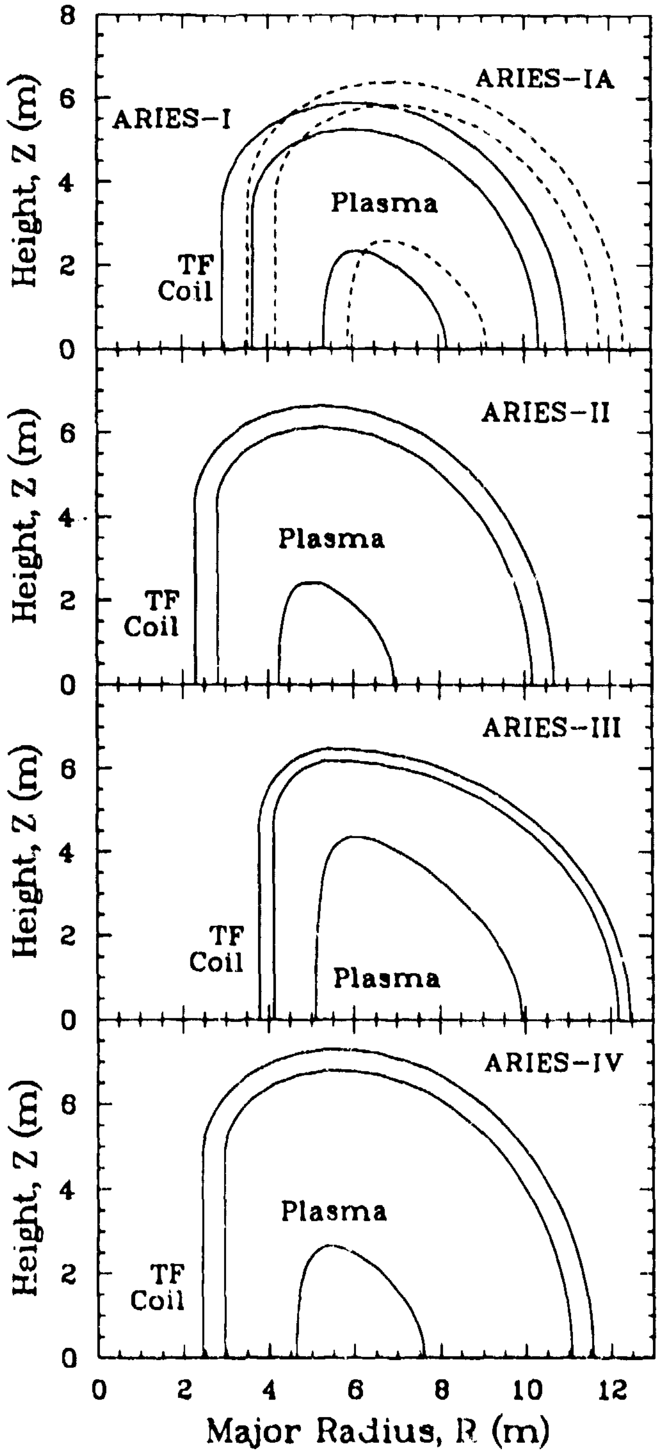

Fig. 1. The elevation view of the upper-half plane of the various ARIES designs.

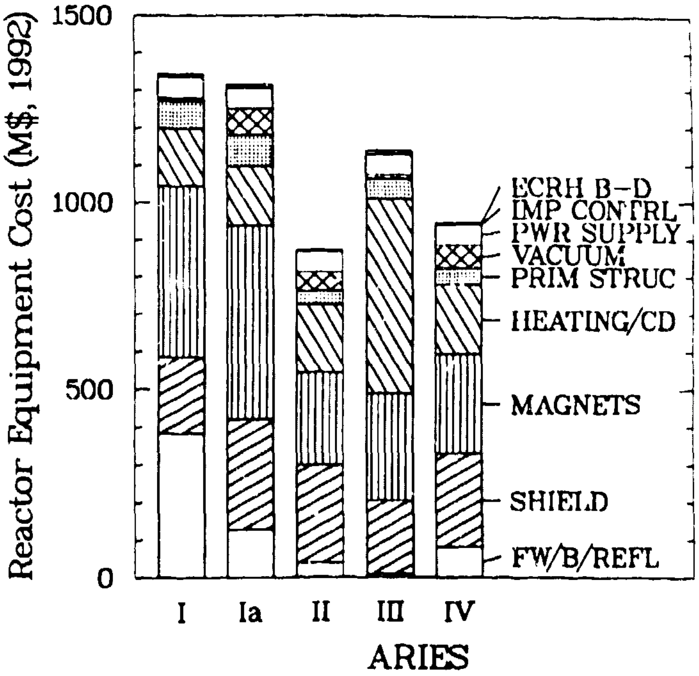

Fig. 2. Breakdown of the Reactor Equipment Cost (Account 22.1) for each of the ARIES designs.

of ARIES-III is 5% lower than for ARIES-I is that the ARIES-III design receives a large credit in Reactor Equipment cost for not having a T-breeding blanket, but also receives a nearly as large debit for the large NBI system that drives 25% of the 29-MA plasma current. The ARIES-III design receives a second credit in COE for not having a blanket to replace that is nearly offset by the debit for ^3He fuel. Although the neutron wal loading is low, ARIES-III could not qualify for the highest safety rate[7], $LSA = 1$. The ARIES-II and -IV designs are the smallest ARIES reactors because of the higher beta relative to ARIES-I and because of the higher fusion-reaction cross section of D-T fuel relative to D-^{3}He. The higher beta of the SSR relative to the FSR decreases the magnetic field and, hence, the magnet costs, but also reduces the machines size so that the blanket and shield costs are also lower. Since ARIES-II has a higher blanket energy multiplication than ARIES-IV, ARIES-II is smaller and less costly and has a lower COE.

The sensitivity of the COE to perturbations of the ARIES designs is measured by a normalized first derivative, $\Delta COEx/COE\Delta x$ and is shown in Fig. 4. For $|\Delta COEx/COE\Delta x| \leq 0.1$, the departure from optimum is not significant. Most of the optima result from a balance of the cost of recirculating power, Q_E^{-1}, with the cost of mass as measured by mass/power density, MPD^{-1}. The ARIES-II, -III, and IV designs optimize ion temperature, T_i, as increasing current-drive efficiency is balanced against decreasing fusion power density for increasing T_i. The off-optimum T_i of ARIES-I was selected to minimize Q_E^{-1} and to avoid high neutron wall loads and heat loads on the divertor.

An optimum COE exits in plasma minor radius, if unconstrained, as decreased Q_E^{-1} is balanced against decreased MPD for increasing a. The optimum a is larger for ARIES-Ia than for ARIES-I because the mass and unit cost of the blanket and shield are lower for ARIES-Ia, discounting larger reactors. The ARIES-II and -IV designs are most off-optimum in a because of a conservative limit on the peak-field at the TF coils, $B_{TFC} \leq 16$ T; smaller

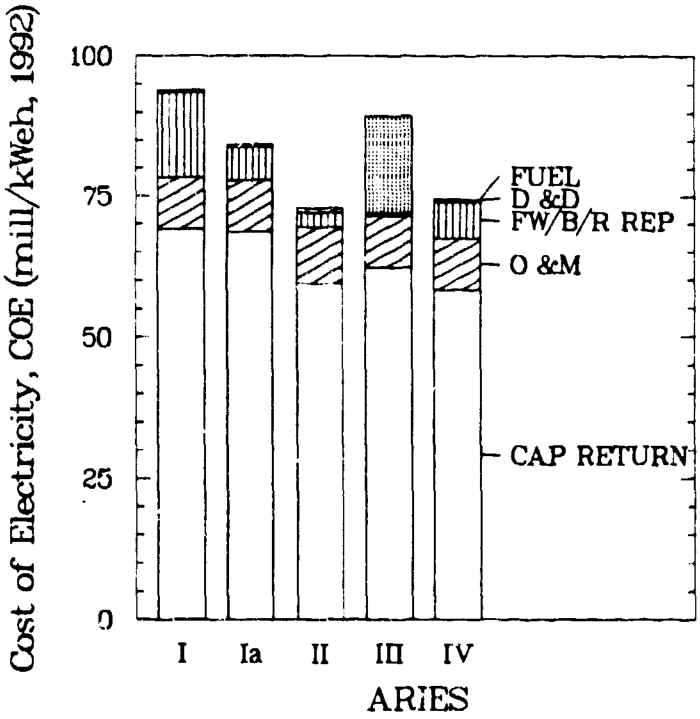

Fig. 3. Breakdown of the Cost of Electricity for each of the ARIES designs.

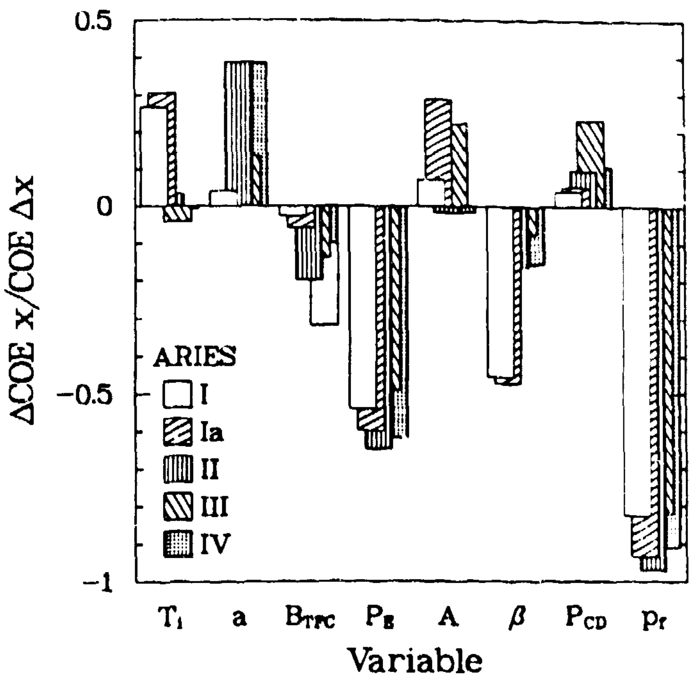

Fig. 4. Per cent change in the cost of electricity resulting from a per cent change about the ARIES designs in ion temperature, T_i; minor plasma radius, a; magnetic field at the TF coil, B_{TFC}; net electric power, P_E; aspect ratio, A; ratio of kinetic-to-magnetic-field pressure, β; current-drive power, P_{CD}; and plant factor, p_f.

a infers larger field. The ARIES-III design is also off-optimum because the neutron wall loading was limited to $\leq$ 0.1 MW/m^2. Since B_{TFC} correlates inversely with a, the B_{TFC} sensitivity is just the inverse of the a sensitivity.

The sensitivity of COE to the net electric power, P_E, illustrates the strong economy of scale for fusion. Typically, reactors are optimized in aspect ratio, A; increasing A reduces MPD and Q_E^{-1}. The enhanced sensitivity of ARIES-Ia over ARIES-I in A illustrates the strong influence that the engineering design exerts on the total reactor design. The ARIES-III design optimizes at lower A, but was constrained to $A = 3$ to avoid the perceived engineering complexity of tight aspect ratio. As expected, increasing β decreases COE and saturates at $\beta \geq 10 - 15\%$.

Only ARIES-III is significantly sensitive to changes in the current-drive power, P_{CD}. The ARIES-II and IV designs have reduced the externally driven currents to a practical minimum that is based on the extent to which the bootstrap current-density profile can be matched to the equilibrium current-density profile. Further improvements of the current-drive scheme for these two designs requires increased efficiency, γ, as shown in Table I.

The COE is most sensitive to the plant availability factor, p_f. For the lack of a data base, a value of $p_f = 0.76$ is adopted from the fission industry. A reduction of p_f to 0.5 would increase the COE of the ARIES designs by ~ 20-30 mill/kWeh.

4. SUMMARY

The ARIES team has completed the design of a series of tokamak reactors that vary the assumed advances in technology and physics. The ARIES-Ia design illustrates the reactor potential of the conventional (first-stability-regime) tokamak physics database and advanced technology. The COE ranges projected for the fissile and fossil competition[8], with a 5% inflation adjustment from 1990 to 1992, are 45-61 and 57-68 mill/kWeh for 1200 and 600 MWe, respectively. The ARIES-Ia design, adjusted to 1200 MWe, has a COE = 76 mill/kWeh, and could not compete even with a small coal plant. The ARIES-Ia COE could be reduced 7% by lowering the T_i, but still would not be competitive. The ARIES-II and -IV designs have the lowest COE. These two designs illustrate the reactor potential of the SSR with only moderate advances in technology. Adjusting the COE of ARIES-II and -IV for P_E = 1200 MWe yields 66 and 67 mill/kWeh, respectively. These designs could compete with a small coal plant, but not large fission reactors. If these two designs also used advanced technology (21- versus 16-T TF coils), the COE would decrease to 62 and 65 mill/kWeh and would be marginally competitive with the high-*COE* end of the competition spectrum. The ARIES-III design shares the same poor economic prognosis as ARIES-I. Furthermore, significant extrapolations beyond the present physics data base (e.g., $H = 8$ and $\tau_p/\tau_E = 2$) are required to burn D-^{3}He fuel in tokamaks as presently understood or envisioned.

Reductions in COE have been demonstrated for improvements in: blanket design ($\sim$ 11%), magnet technology ($\leq$ 6%), and safety credits (9-13%). A comparable reduction is possible for improved physics (12-14%) of the SSR ARIES-IV relative to the FSR ARIES-Ia. However, ($\sim$ 10%) of this improvement is attributable to the T_i optimization of ARIES-IV. Consequently, a marginally attractive tokamak reactor is possible and requires the SSR for high beta and bootstrap current in addition to optimal blanket design, advanced coil technology, maximum credit for safety, and design parameter optimization. Future efforts to improve tokamak reactor should focus on increasing β.

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