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A Systems Assessment of the Five Starlite Tokamak Power Plants

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ABSTRACT

The ARIES team has assessed the power-plant attractiveness of the following five tokamak physics regimes: 1) steady state, first stability regime; 2) pulsed, first stability regime; 3) steady state, second stability regime; 4) steady state, reversed shear; and 5) steady state, low aspect ratio. Cost-based systems analysis of these five tokamak physics regimes suggests that an electric power plant based upon a reversed-shear tokamak is significantly more economical than one based on any of the other four physics regimes. Details of this comparative systems analysis are described herein.

I. INTRODUCTION

The ARIES team, as part of the Starlite project, has evaluated¹ the following five tokamak physics regimes as electricity generating power plants: 1) a steady state, first stability regime (FS) similar to ARIES-I;² 2) a pulsed, first stability regime (PU) similar to PULSAR;³ 3) a steady state, second stability regime (SS) similar to ARIES-II/IV;⁴ 4) a steady state, reversed-shear tokamak (RS); and 5) a steady state, low-aspect-ratio tokamak (LAR). As part of the systems analysis, cost-optimized designs are generated with the ARIES Systems Code (ASC)^{3,4} for each candidate. The drivers in the tradeoffs that determine the optimal design are unique for each tokamak regime. The mass of the fusion power core (FPC) is minimized in the optimal pulsed design; whereas, minimal FPC mass must be balanced against minimal recirculating power for the optimal steady-state designs. The dominant cost can also be affected by the physics regime. Magnets dominate the cost of all tokamaks but one; SS is dominated by

current-drive cost. This SS result differs significantly from earlier results,^{4,5} wherein the current-drive power is a factor of three lower. The RS tokamak is projected to be the most economically attractive power plant of those considered. The design changes since an initial comparison,⁵ as well as the details of the final comparison of these five tokamak physics regimes¹ are presented herein.

II. MODEL

The (ASC)^{3,4} examines a spectrum of tokamak power-plant options (*e.g.*, different blankets, beta limits, coil scalings, *etc.*). New ASC capabilities include the addition of reverse shear and low-A tokamak physics regimes. The essential features and notation of the ASC models are summarized below.

The axisymmetric plasma is characterized by the major toroidal radius, R_T ; equatorial-plane minor radius, a_p ; vertical elongation, κ ; and triangularity, δ . The plasma beta for FS is constrained by a Troyon relation: $\beta \equiv 2\mu_0 \langle p \rangle / B_{\phi 0}^2 = C_T I_{\phi} / a_p B_T$; where $\langle p \rangle$ is the volume averaged plasma pressure, B_T is the on-axis vacuum toroidal magnetic field, and the constant C_T is limited by ballooning stability. For SS, $\beta \equiv \epsilon(\epsilon\beta_p)S^2/q_*^2$ to illustrate the effects of stability; where $\epsilon \equiv A^{-1} = a_p/R_T$, β_p is the poloidal beta, $S^2 = (1 + \kappa^2)/2$, and q_* is a circularized safety factor. An equilibrium limit constrains $\epsilon\beta_p \leq 1.85$, high-n ballooning stability constrains $q_* \geq 4.6$, and vertical stability limits $\kappa \leq 2$. Numerical fits to a series of equilibrium and stability calculations are used to determine the normalized beta, β_N , in the scaling $\beta = 0.05\epsilon\beta_N S^2/q_*$ used for PU, RS, and LAR. The β_N scaling for RS has increased relative to the value reported in Ref. 5 ($\beta_N = 4.8$ versus 4.1%),

because the RS stabilizing shell was moved closer to the plasma to be at the same relative location as for SS. Also, the β_N scaling for LAR has decreased relative to its earlier value⁵ ($\beta_N = 6.4$ versus 7.9%) to decrease the current-drive power ($P_{CD} = 7$ versus 432 MW). All β are reduced 10 % from the stability limits as a disruption safety margin. The FS and PU tokamaks represent near-term physics; PU has a lower β_N because of profile restrictions imposed by inductive current drive, as is indicated in Table I. Advanced physics is represented by SS and RS, and super-advanced physics is represented by LAR.

Central to the ASC is a zero-dimensional, steady-state plasma-power-balance model⁶ that includes separate ion and electron energy balance; particle continuity; a specified impurity fraction; charge balance; and a β constraint. The zero-dimensional equations are derived from a radial average over plasma profiles that preserve the peak-to-average ratios of pressure and density obtained from detailed equilibrium and current-drive calculations. The fractional fusion power deposited to the ions is calculated from time integrals of fusion-product slowing down rates. The energy confinement time, τ_E , derived from power balance is monitored as the ratio $H = \tau_E / \tau_{89P}$; where τ_{89P} is the confinement time predicted by the ITER-89P scaling⁷. The particle confinement time including recycling is assumed to be $\tau_p^* = 10\tau_E$.

A fraction f_{BC} of the plasma current is sustained by the pressure-gradient-driven bootstrap effect. For both FS and PU, $f_{BC} \propto \epsilon^{1/2}\beta_p < 1$ because of inherently low $\epsilon\beta_p$. The pressure gradient is sufficiently large for RS and $\epsilon\beta_p$ is sufficiently large for SS and LAR that f_{BC} can exceed unity. Even if $f_{BC} \sim 1$ globally, externally driven current is necessary to match the radial profile of the total (bootstrap and externally-driven) current density with the required equilibrium current-density profile. The location of any mismatch between the bootstrap and equilibrium current-density profiles determines the rf frequency and power of the external current drive. Detailed equilibrium and ray-tracing calculations are used to determine the normalized current-drive efficiency, $\gamma_B = n_e 10^{-20} R_T I_p / P_{CD}$, for each design. The SS γ_B has been lowered from its previous value^{4,5} (from 1.36 to 0.49 10^{20} A/W m²), as a result of using a more accurate bootstrap model; profile optimization may recover some of the lost γ_B . Also, the γ_B for RS and LAR have increased since Ref. 5, because of further optimization of both β_N and γ_B . The LAR γ_B may be overly optimistic, because it does not include any power that might be needed to maintain

the desired profiles. The FS and SS designs use a combination of ICRF and LHRF to drive current. High-frequency, fast wave (HFFW) current drive at approximately the twentieth ion cyclotron harmonic is used for both RS and LAR: 500-900 MHz and 250 MHz, respectively. The PU tokamak on the other hand inductively drives current by using the PF coils as a transformer.

To compare these tokamaks on a purely physics basis, all designs use the same blanket and shield. The structural material is V4Cr4Ti, and liquid-Li is both tritium breeder and coolant. The blanket and shield design is a refinement to the V5Cr5Ti design used for ARIES-II⁴ and Ref. 5 and was chosen for its high-neutron-wall-loading (*i.e.*, $\dot{I}_w \leq 10.4$ MW/m²) and high-thermal-conversion-efficiency (*i.e.*, $\eta_{TH} = 0.46$) capabilities. The combined blanket and shield thickness is ~ 1.0 m inboard and ~ 1.3 m outboard. The blanket multiplication was lowered from 1.39⁵ to 1.37 to permit replacement of expensive Vanadium (300 \$/kg, in 1992\$) with cheaper modified HT9 (68 \$/kg, 35 \$/kg was used in Ref. 5) in the outermost portion of the shield. Also, the first-wall fluence lifetime was reduced from 16.4⁵ to 12 MW y/m². The PU outboard shield is also used to provide 200 s of inexpensive (~ 30 M\$, or ~ 80 \$/MJ) thermal storage that is used to maintain constant electrical output between plasma-burn periods; A consequence of using the shield for thermal storage is a 3 % reduction in blanket energy multiplication. A gap between the shield and TF coils on the outboard side is provided in all designs to allow blanket sectors to be removed horizontally between TF coils. A scrapeoff thickness of 0.10 m is used, except in SS and RS, which have greater compression of adjacent flux surfaces at the equatorial plane relative to the field null and can use 0.05 m.

Constant-tension, D-shaped TF coils are used in all designs but LAR. The LAR design uses a normal Cu conductor. The LAR centerpost is flared to conform to the shape of the plasma (the ratio of average to equatorial-plane cross sectional areas is ~ 2) and is protected by 0.3 m of shield to ensure Class C waste disposal. Even then the centerpost must be changed yearly to prevent build up of transmutation products that increase resistivity. For the remaining designs, the superconductor is Nb₃Sn, and is limited to $B_{TF} \leq 16$ T. Cyclic-fatigue effects require the engineering current density, j_{TF} , be decreased for pulsed operation as the number of pulses are increased to ensure survival of the TF coils

TABLE I Parameters for Commercial-Power-Plant Embodiments of Five Tokamak Physics Regimes.

Parameter	FS	PU	RS	SS	LAR
Length of burn, τ_B (h)	∞	2.5	∞	∞	∞
Plasma aspect ratio, $A = R_T/a_p$	4.0	4.0	4.5	4.0	1.25
Major toroidal radius, R_T (m)	7.96	8.68	5.04	6.40	5.00
Plasma minor radius, a_p (m)	1.99	2.17	1.26	1.60	4.00
Plasma elongation, κ_x	1.81	1.80	1.99	2.03	3.40
Plasma triangularity, δ_x	.71	0.50	0.69	.67	0.55
Circularized safety factor, q_*	3.77	2.40	2.37	4.60	3.54
Stability parameter, $\epsilon\beta_p$	.54	0.32	0.56	1.22	1.14
Normalized beta, β_N (%)	2.88	2.70	4.76	5.28	6.42
Toroidal beta, β (%)	2.03	2.50	5.31	3.04	36.3
Poloidal beta, β_p	2.17	1.30	2.26	3.64	1.42
Ion temperature, T_i (keV)	14.0	14.0	14.0	12.0	12.0
Ion density, n_i ($10^{20}/\text{m}^3$)	1.12	1.00	2.07	1.70	1.00
Lawson parameter, $n_i\tau_E$ ($10^{20}\text{s}/\text{m}^3$)	1.71	4.11	2.58	1.93	4.89
ITER-89P scaling ⁷ multiplier, H	1.71	2.38	2.40	2.47	3.02
Radiation fraction, f_{RAD}	0.16	0.31	0.19	0.14	0.32
Plasma current, I_p (MA)	12.6	15.0	10.3	7.72	40.1
Bootstrap-current fraction, f_{BC}	0.57	0.34	0.89	> 1	≈ 1.00
CD efficiency, γ_B (10^{20} A/W m^2)	0.56	NA	2.02	0.49	34.2
CD power to plasma, P_{CD} (MW)	237.6	0	64.7	199.1	7.3
On-axis toroidal field, B_T (T)	8.96	7.46	7.35	8.37	1.77
Peak field at TF coil, B_{TF} (T)	16.0	13.1	15.7	15.9	16.0
TF-coil current density, j_{TF} (MA/ m^2)	25.9	15.3	34.5	29.5	45.1
TF-coil ohmic losses, P_{TF} (MW)	0	0	0	0	1565
Peak neutron load, $\hat{I}_w$ (MW/ m^2)	2.62	1.83	5.74	4.72	3.14
Normalized divertor heat flux, P_{TR}/R_T (MW/m)	71.2	29.5	71.3	89.0	124.2
Blanket energy multiplication, M_N	1.37	1.35	1.37	1.37	1.37
Recirculating power fraction, $\epsilon(1/Q_E)$	0.29	0.06	0.13	0.33	0.63
Mass power density, MPD (kWe/tonne)	36.6	22.6	70.8	49.1	26.2
Cost of electricity (mill/kWeh, 1992\$):					
total COE w/ safety credits (LSA=2)	99.66	130.22	69.72	92.62	115.97
total COE w/o safety credits (LSA=4)	112.94	147.35	79.35	104.91	130.87

for the plant lifetime. For PU the TF-coil bucking forces are transmitted through the inboard PF-coil stack to the bucking cylinder; whereas the bucking cylinder is positioned between the TF and PF coils for the conventional-A, steady-state designs. The LAR design has no bucking cylinder.

A discrete PF-coil model³ is used for PU, RS, and LAR; the ARIES PF-coil model⁴ that lumps the PF-coils into divertor and equilibrium-field coil pairs is used for FS and SS. The discrete PF-coil model generates a PF-coil set with minimum stored energy that produces the required equilibrium field at full and partial beta with full plasma current and produces the magnetic-flux swing required: to induce

and sustain the plasma current for pulsed plasmas; and to induce the plasma current for steady-state, conventional-A plasmas. No flux-swing requirement is imposed for LAR. The stress is determined in keys positioned between inboard (straight) legs of pulsed TF coils to react the TF-coil overturning forces. A simplified circuit model is used to determine the power-supply requirements (*i.e.*, reactive power) for pulsed operation.

The ASC costing algorithm allows for a detailed cost breakdown to four levels. The cost scalings used are consistent with U.S. fission nuclear-reactor experience⁸. Credits for appropriate Levels of Safety Assurance (LSA)⁹ are included.

Fig. 1. Reactor Equipment Costs for commercial-power-plant embodiments of five tokamak physics regimes.

III. RESULTS

Parameters that are generated with the ASC for cost-optimized, commercial power plants are given in Table I for all five tokamaks. Although the COE optimum aspect ratio is $A < 4$, the aspect ratio has been limited to $A = 4$ for FS, PU, RS, and SS to improve the layout, accessibility, and maintainability of the FPC with little impact on the COE. The aspect ratio for LAR has been taken from Ref. 5. All designs have been optimized in minor radius. The three all-superconducting, steady-state designs (FS, RS, and SS) optimize the COE at the minimum minor radius at which the peak field at the TF coil is $B_{TF} = 16$ T. Because of the low recirculating-power fraction, optimal PU COE occurs at the minor radius that maximizes mass power density, MPD (kW/tonne); at smaller radii MPD decreases because the TF-coil mass increases, and at larger radii MPD decreases because the shield volume increases. The optimum plasma temperature for steady-state tokamaks generally results from a trade off between increasing γ_B and decreasing fusion power density with increasing temperature. For PU the optimum temperature results from a trade off between decreasing fusion power density and decreasing plasma resistance with increasing temperature.

The Reactor Equipment Costs, which in total approximate the FPC cost, are given in Fig. 1.

Fig. 2. Total Direct Costs for commercial-power-plant embodiments of five tokamak physics regimes.

The PU design has the largest FPC cost, which is dominated by magnet cost. The high magnet cost results from extra structure required to fortify against cyclic-fatigue effects. In spite of a larger β_N and β , LAR has a larger FPC cost relative to RS and SS. The magnet cost dominates the LAR FPC cost because extra conductor must be added to the normal conducting TF coil to minimize ohmic dissipation and recirculating power. Because of lower β , FS has a more expensive FPC than either RS or SS. The RS FPC costs is lower than for SS because of the high current-drive cost for SS. Compiling the Total Direct Costs (TDC) indicates that LAR is further penalized for a large recirculating power with a relatively larger turbine-plant-equipment cost, as is shown in Fig. 2.

The COE for each tokamak power plant is given in Fig. 3. The Starlite requirement (≤ 80 mill/kWeh) and goal (≤ 65 mill/kWeh) for the COE^{1,11} of a commercial power plant are also indicated in Fig. 2. Neither LAR, PU, FS, nor SS meet the COE requirement; LAR fails because of its large recirculating power and associated costs, PU fails because of its low β and MPD and cost penalties associated with pulsed operation, FS fails because of its low β and MPD, and SS fails because of its high current-drive power. The COE requirement is met only by RS because of high β and MPD and low current-drive and recirculating powers. None of the tokamak regimes considered surpasses the COE goal.

Fig. 3. Cost of Electricity for commercial-power-plant embodiments of five tokamak physics regimes. The Starlite COE requirement and goal for a commercial power plant^{1,11} are also indicated.

III. SUMMARY

The ARIES team has generated cost-optimized design parameters for commercial power plants with common engineering features that are based on the following five tokamak physics regimes: 1) a steady state, first stability regime (FS) similar to ARIES-I²; 2) a pulsed, first stability regime (PU) similar to PULSAR³; 3) a steady state, second stability regime (SS) similar to ARIES-II/IV⁴; 4) a steady state, reversed shear tokamak (RS); and 5) a steady state, low aspect ratio tokamak (LAR). Systems analyses indicate that only RS meets the Starlite requirement on COE for a commercial power plant. For this reason, the ARIES team is undertaking a conceptual design of a commercial power plant based on reversed-shear tokamak physics.

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