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A Comparison of Steady-State ARIES and Pulsed PULSAR Tokamak Power Plants

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ABSTRACT

The multi-institutional ARIES study has completed a series of three steady-state and two pulsed cost-optimized conceptual designs of commercial tokamak fusion power plants that vary the level of assumed advances in technology and physics. The cost benefits of various design options are compared quantitatively. Possible means to improve the economic competitiveness of fusion are suggested.

I. INTRODUCTION

After having completed a series¹⁻³ of conceptual designs of steady-state tokamak power plants that identified current drive as the major design and cost driver,⁴ the multi-institutional ARIES (Advanced Reactor Innovation and Evaluation Study) project examined two tokamak conceptual designs for the PULSed Advanced Reactor (PULSAR).⁵ The primary difference between the two PULSAR designs is the structural material/coolant selected: SiC/He for PULSAR-I and V/Li for PULSAR-II. These PULSAR designs are compared on a common physics, engineering, ES&H, and economic basis to only the DT-fueled ARIES designs: the first-stability-regime (FSR), SiC/He ARIES-I design^{1,3} and the second-stability-regime (SSR, higher plasma beta), V/Li ARIES-II and SiC/He ARIES-IV designs.³ Differences between steady-state *versus* pulsed operation are manifested mainly through cyclic-fatigue effects, the need for thermal storage, and pulsed power supplies. Another major difference between the ARIES and PULSAR designs is the methodology for maintaining current. In the ARIES designs a large fraction (f_{BC}) of the plasma current is assumed to be

driven by the neoclassical bootstrap effect and the remaining current is driven externally by an rf system that can recirculate significant electrical power; $f_{BC} \sim 0.7$ for ARIES-I and $f_{BC} \sim 0.9$ for ARIES-II/IV. In PULSAR an OH-coil transformer induces all and sustains less than half ($f_{BC} = 0.4$) the plasma current for an optimized burn cycle.

Different strategies then result for economically optimizing the ARIES and PULSAR designs. The steady-state ARIES designs balance recirculating power [mainly, added balance-of-plant (BOP) and rf power supplies] against fusion-power-core (FPC) mass power density, MPD. In contrast PULSAR with fixed recirculating power need maximize only MPD. However, the cost optimal designs for both steady-state and pulsed tokamaks strive for minimal plasma current.

II. MODEL

The ARIES systems code (ASC)³ examines a spectrum of tokamak reactor options (*e.g.*, different blankets and beta limits). The ASC has evolved during the ARIES and PULSAR projects to account for refinements of the physics and engineering models. All designs reported herein have been (re)analyzed with the latest version of ASC and are presented here for comparison on a common basis.

The updated models used in the ASC are described in Ref. 3, 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 beta for the

FSR ARIES-I is constrained by a Troyon-type relation: $\beta \equiv 2\mu_0 \langle p \rangle / B_{\phi 0}^2 = C_T I_{\phi} / a B_{\phi 0}$; where $\langle p \rangle$ 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 limited by ballooning stability. For the SSR ARIES-II/IV, the beta has been reformulated as $\beta \equiv \epsilon(\epsilon\beta_{\theta})S^2/q_*^2$ to illustrate the effects of stability; 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 $\epsilon\beta_{\theta} \leq 1.85$, high-n ballooning stability constrains $q_* \geq 4.6$, and vertical stability limits $\kappa \leq 2$. A numerical fit to a series of equilibrium and stability calculations⁵ is used to determine beta for PULSAR.

Central to the ASC is a zero-dimensional, steady-state plasma-power-balance model⁶ that includes ion and electron energy balance; particle continuity; a specified impurity fraction; charge balance; and a plasma beta 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 in the ions is calculated from time integrals of fusion-product slowing down rates. The energy confinement time, τ_E , that is derived from power balance is monitored as a ratio $H = \tau_E/\tau_{89P}$; where τ_{89P} is the confinement time suggested by the ITER-89P scaling.⁷

All designs rely on some fraction, f_{BC} , of the plasma current being driven internally by the pressure-gradient-driven bootstrap effect. In both (FSR) ARIES-I^{1,3} and PULSAR⁴, $f_{BC} \propto \epsilon^{1/2}\beta_{\theta}$. In the SSR, $\epsilon\beta_{\theta}$ is sufficiently large that f_{BC} can exceed unity in the FSR scaling. Even if $f_{BC} \sim 1$ globally, externally driven current is necessary to match the total driven radial current-density profile with the required equilibrium current-density profile; an on-axis seed current, a current to cancel the bootstrap overdrive at intermediate radii, and an edge current must all be driven externally. The ARIES-I and ARIES-II/IV designs use a combination of ICRF and LHRF for current drive. A temperature dependent model for each component of the externally driven current is used for the ARIES-II/IV designs. The PULSAR designs inductively drive current by using the PF coils as a transformer.

Each design has specific blanket, shield, and coil models. The structural material in the blanket and shield of ARIES-I and -IV and PULSAR-I is a SiC composite with helium coolant. The T-

Fig. 1. An elevation view of PULSAR-II.

breeding material is Li_2O for all (for comparative purposes) SiC designs, although Li_2ZrO_3 was originally used in ARIES-I¹ and expensive isotopically tailored was needed to reduce radioactive inventory and release hazard. The ARIES-IV and PULSAR-II designs use V5Cr5Ti as structural material with a liquid-Li coolant. The V5Cr5Ti blanket and shields are ~ 1.0 and ~ 1.5 m thick inboard and outboard, respectively; the SiC blanket and shields are ~ 1.3 and ~ 1.8 m thick inboard and outboard, respectively. The PULSAR shields are also used to provide 200 s of cheap (~ 30 M\$) thermal storage that is used to maintain constant electrical output; additional thermal storage beyond 200 s is charged at 37 M\$/s. A gap between the shield and TF coil on the outboard side is provided in all (for comparative purposes) designs to allow blanket sectors to be removed horizontally between TF coils; a vertical maintenance scheme was originally used in ARIES-I.¹ A scrapeoff thicknesses of 0.10 m is used in all designs, except the SSR ARIES-II/IV designs that have greater compression of adjacent flux surfaces at the equatorial plane relative to the field null. Constant-tension TF coils are used in all designs. The TF-coil current density is increased for PULSAR to account for cyclic-fatigue effects. A PF-coil model was developed for PULSAR and is shown in Fig. 1 that produces a PF-coil set with minimum stored energy for the necessary Volt-seconds. The model also determines the stress in the keys between inboard (straight) legs of the TF

Fig. 2. Fusion-power-core (FPC) figure-of-revolution (refer to centerline, $R=0$) cross sections for the 1-GWe PULSAR-I, updated ARIES-I' with 16-T and 19-T TF coils, and ARIES-IV tokamak power plants. Also shown is a pressurized-water fission reactor (PWR) of comparable (1.1 GWe) net electrical power.¹¹

coils⁸ that react the TF-coil overturning forces and the power supply requirements (VA).

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 experience.⁹ Credits for appropriate Levels of Safety Assurance (LSA)¹⁰ are included.

III. RESULTS

Power-plant parameters are given in Table I for: an updated ARIES-I (ARIES-I') with and without high-field TF coils, ARIES-II and -IV, and PULSAR-I and -II. A clearer comparison of steady state *versus* pulsed operation is obtained by focusing on the SiC designs that are shown in Fig. 2. Of the SiC designs PULSAR-I is the largest tokamak and most expensive, as is shown in Fig. 3. The PULSAR-I TF coils are designed at a low current density so that they can withstand cyclic fatigue effects for the lifetime of the power plant (30 full power yr) and subsequently are the most expensive part of the tokamak. In PULSAR-I the cost of the TF coils and the COE are minimized by decreasing the field at the coil, which raises the current density and lowers the coil costs, and at the plasma by increasing the size of the tokamak relative to the steady-state ARIES designs at the same net electrical power, $P_E = 1$ GWe; for constant power $\beta^2 B^4 A a_p^3 \sim \text{constant}$. The rf (both heating and current drive) costs can be reduced, but not eliminated in PULSAR-I; the plasma is heated to ignition in all designs with rf. The rf cost savings for PULSAR-I are less than the cost penalty associated

Fig. 3. Reactor Equipment (RP) cost (the tokamak part of the power plant) for the 1-GWe PULSAR-I, updated ARIES-I' with high- and moderate-field TF coils, and ARIES-IV tokamak power plants.

with the power supplies required for pulsed operation of the PF coils. Even though the unit cost of high-field (19-T) TF coils are $\sim 10\%$ more expensive than for moderate-field (16-T) TF coils, high-field coils reduce the COE by 7% for the low beta ARIES-I' design by allowing higher plasma field and smaller plasma minor radii, a_p . Comparing the 16-T ARIES-I' and ARIES-IV the benefits of SSR are higher beta and f_{BC} and a reduction in size and in COE by 19% relative to FSR.

The COE projected for ARIES-II and -IV and PULSAR-I and -II is shown in Fig. 4 in comparison with the COE projected for various competitors of fusion. The best of the fusion designs examined herein (*i.e.*, ARIES-IV) is competitive with coal, but is significantly more expensive than the advanced pressurized water reactor, APWR. Increasing the net electrical power would decrease the COE, but has several drawbacks: increased neutron wall loading; an even higher total capital cost; and reduced reliability.

Additional means to reduce COE are shown in Fig. 5. They include increasing the plasma beta and/or Troyon coefficient, while maintaining a $f_{BC} \sim$

TABLE I Comparison of Reactor Parameters for ARIES-I' (19 T), -I' (16 T), -II, and -IV and PULSAR-I and II.

Parameter	ARIES				PULSAR	
	I'	I'	II	IV	I	II
Stability regime	FSR	FSR	SSR	SSR	FSR	FSR
Length of burn, τ_B (h)	∞	∞	∞	∞	2.5	2.5
Major toroidal radius, R_T (m)	6.17	7.40	5.60	6.04	9.20	7.91
Minor plasma radius, a (m)	1.54	1.85	1.40	1.51	2.30	1.98
Plasma elongation, κ	1.80	1.80	2.03	2.03	1.80	1.80
Plasma triangularity, δ	0.70	0.70	0.67	0.67	0.50	0.50
Plasma aspect ratio, $A = R_T/a$	4.0	4.0	4.0	4.0	4.0	4.0
Plasma-edge safety factor, q	4.5	4.5	12.2	12.2	3.54	3.54
Peak-to-average density ratio, n_0/n	1.30	1.30	1.12	1.12	1.30	1.30
Peak-to-average temperature ratio, T_0/T	1.90	1.90	2.65	2.65	1.70	1.70
Troyon coefficient, C_T (Tm/MA)	0.032	0.032	0.059	0.059	0.030	0.030
Plasma beta, β	0.019	0.023	0.034	0.034	0.028	0.028
Plasma poloidal beta, β_θ	2.41	2.41	5.40	5.40	1.44	1.44
Density-wt. average ion temperature, T_i (keV)	12	12	10	10	14	14
Density-wt. average electron temperature, T_e (keV)	13.0	13.0	10.3	10.3	15.0	15.4
Average ion density, $n_i(10^{20}/m^3)$	1.73	1.31	2.15	1.97	0.86	1.03
Average electron density, $n_e(10^{20}/m^3)$	1.56	1.46	2.53	1.02	1.20	
Particle-to-energy confinement time ratio, τ_p/τ_E	4	4	9.8	9.15	4	4
Ion-to-electron energy confinement time ratio, τ_{Ei}/τ_{Ee}	1	1	1	1	0.5	0.5
Lawson parameter, $n_i\tau_E(10^{20}s/m^3)$	1.70	1.72	2.71	2.90	3.30	2.92
ITER-89P confinement-time multiplier ⁵ , H	1.76	1.80	3.07	3.15	2.38	2.29
Plasma gain, $Q_p = P_F/P_{CD}$	10.8	11.3	28.9	29.8	∞	∞
On-axis toroidal field, $B_{\phi 0}$ (T)	9.64	8.39	7.97	7.63	6.65	7.31
TF-coil field, $B_{\phi c}$ (T)	19.8	16.0	15.9	15.9	11.6	12.8
TF-coil current density, $j_{\phi 0}$ (T)	24.3	26.7	31.6	30.0	18.2	17.9
Radiation fraction, f_{RAD}	0.18	0.18	0.18	0.23	0.30	0.21
Plasma current, I_ϕ (MA)	10.5	10.9	29.9	6.64	14.2	13.4
Bootstrap-current fraction, f_{BC}	0.65	0.65	0.87	0.87	0.37	0.37
Current-drive efficiency, γ (10^{19} A/W-m ²)	2.16	2.16	1.83	1.81	NA	NA
Current-drive power to plasma, P_{CD} (MW)	202.5	192.7	66.1	68.0	NA	NA
Average neutron wall loading, I_W (MW/m ²)	2.99	2.10	2.90	2.67	1.10	1.32
Blanket neutron energy multiplication, M_N	1.23	1.23	1.38	1.23	1.17	1.35
Structural material	SiC	SiC	V5Cr5Ti	SiC	SiC	V5Cr5Ti
Coolant	He	He	Li	He	He	Li
Thermal-conversion efficiency, η_{TH}	0.49	0.49	0.46	0.49	0.49	0.46
Thermal power, P_{TH} (GWt)	2.87	2.84	2.57	2.53	2.31	2.36
Gross electrical power, P_{ET} (GWe)	1.40	1.39	1.18	1.24	1.11	1.06
Net electrical power, P_E (GWe)	1.0	1.0	1.0	1.0	1.0	1.0
Recirculating power fraction, $1/Q_E$	0.29	0.28	0.15	0.19	0.10	0.06
Plant efficiency, $\eta_p = \eta_{TH}(1 - 1/Q_E)$	0.35	0.35	0.39	0.40	0.44	0.43
FPC mass power density, MPD (kWe/tonne)	87.4	92.6	70.2	111	41.2	42.4
Level of safety assurance ⁶ , LSA	1	1	2	2	1	2
Reactor Equipment cost, (B 1992\$)	1.57	1.81	1.36	1.30	2.40	2.05
Total direct cost, TDC (B 1992\$)	2.27	2.52	2.16	1.96	3.40	3.34
Total cost (B 1992\$)	4.24	4.70	4.17	3.67	6.36	6.44
Cost of electricity, COE (1992\$ mill/kWeh):						
w/ safety credits	76	82	74	68	105	106
w/o safety credits	101	108	84	90	137	120

Fig. 4. The cost of electricity in 1992 \$ for ARIES-II and -IV as a function of the net electrical power. Each point along a curve represents the COE optimum in minor radius, a_p . Also shown are the competition from Ref. 12: coal; pressurized water reactor-best experience, PWR-BE; improved pressurized water reactor, IPWR; and advanced pressurized water reactor, APWR. Additional competitors shown are wind¹³ (corrected for 3 % inflation between 1992 and 1993) and a target for solar¹⁴.

1; increasing the plant factor; and decreasing the unit cost of the shield.

IV. SUMMARY AND CONCLUSIONS

The disparity in the COE between ARIES-IV and PULSAR-I is so large that investigation of steady-state current drive is mandated. Furthermore, the reduction in COE for SSR relative to FSR is significant and warrants experimental exploration of SSR. Further reductions in the COE for fusion are required for market penetration. Several physics (e.g., β) and engineering (e.g., p_f and c_s) parameters have been identified that offer the potential for further reductions in the COE.

ACKNOWLEDGMENTS

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Fig. 5. Per cent change in the cost of electricity for ARIES-IV resulting from per cent changes about the design point those parameters having the greatest potential to reduce COE: plasma beta, β ; Troyon coefficient, C_T ; bootstrap-current fraction, f_{BC} ; the plant (capacity) factor, p_f ; the net electrical power, P_E ; and the cost of the shield, c_s . Each point along a curve, except the a_p curve, represents the COE optimum in minor radius, a_p . See Table I for design values.

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