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THE ARIES-III D-³He TOKAMAK REACTOR: DESIGN-POINT DETERMINATION AND PARAMETRIC STUDIES†

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Abstract: The multi-institutional ARIES study has generated a conceptual design of another tokamak fusion reactor in a series that varies the assumed advances in technology and physics. The ARIES-III design uses a D-³He fuel cycle and requires advances in technology and physics for economical attractiveness. The optimal design was characterized through systems analyses for eventual conceptual engineering design. Results from the systems analysis are summarized, and a comparison with the high-field, D-T fueled ARIES-I is included.

INTRODUCTION

The Advanced Reactor Innovation and Evaluation Study (ARIES)¹ is a multi-year, multi-institutional exploration of several tokamak-reactor visions emphasizing economic, safety, and environmental features. The first design completed, ARIES-I², is a D-T fueled reactor that uses conventional physics and advanced technology, and the second completed design reported herein, ARIES-III³, uses D-³He fuel and requires advances both in engineering and physics. The ARIES-II design is in progress and is a D-T fueled reactor based on advanced physics and conventional engineering. The technological advances invoked for ARIES-III include: high-efficiency ($\eta_{CD} = 0.68$), energetic (3-6 MeV) neutral beams for current drive; advanced, high current-density (40 MA/m², averaged over TF coil) superconducting coils; and a low activation HT-9 shield (a tritium breeding blanket is unnecessary). Economics dictates physics operation in a high-beta ($\beta = 0.24$), high-safety-factor ($q_0 = 1.95$, $q_{edge} = 6.85$), second-stability regime (SSR) to achieve acceptable power density at moderate magnetic field ($B_{\phi 0} = 7.6$ T) and relatively low plasma current ($I_p = 29.9$ MA). The plasma density profile is optimized to minimize bootstrap-current "overdrive" (a characteristic of the high $\epsilon\beta_s$ SSR) to 25%; the externally driven current is 7.5 MA. Furthermore, a large energy-confinement-time enhancement factor of $H = 7.2$ over the ITER-89P scaling⁴ is required. The ARIES-III design point was increased in size (major radius $R_T = 7.5$ m and minor radius $a_p = 2.5$ m) relative to the cost-of-electricity (COE) minimum at a 2% penalty in COE to ensure a low (DD, DT) peak neutron wall loading ($I_w = 0.1$ MW/m²) and low activation, in an attempt to achieve the most favorable safety rating (level of safety assurance⁵ LSA = 1). Sensitivity studies about the COE optimum indicate the limited design window available to D-³He tokamak reactors. A common-basis comparison of the earlier ARIES-I design² and a first-stability-regime variant of ARIES-III is made.

MODEL

The ARIES-III design was parametrically analyzed with the ARIES system code (ASC)², which examines different fuel mixes, blankets, and beta limits (i.e., value of the Troyon coefficient C_T). However, the reduced volumetric fusion-product heating rate of D-³He relative to D-T severely restricts the plasma operating window, which made necessary one major modification to ASC: the insertion of the MakNTAU plasma power balance code⁶ into ASC. The MakNTAU subroutine package is based on a zero-dimensional, steady-state plasma model 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. The fractional fusion power deposited in the ions is calculated from time integrals of the fusion-product slowing down rates. The parameters input into the MakNTAU model include the ion temperature, T_i ; the toroidal plasma current, I_p ; 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, $\phi_s H_e + \phi_T + \phi_D = 1$. The computed parameters include ion density fractions; the electron temperature, T_e ; the Lawson parameter, $n_i \tau_{Ei}$; and the suprathermal beta. The required τ_E is then expressed as H .

The models used in the ASC are described in Ref. 2, 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 . Standard radial profiles are assumed for density and temperature: $n(r) = n_0[1 - (r/r_p)^2]^{\alpha_n} + n_E$ and $T(r) = T_0[1 - (r/r_p)^2]^{\alpha_T}$, respectively; where r_p is the circularized plasma radius. The plasma toroidal beta is constrained by a Troyon-type relation: $\beta \equiv 2\mu_0 \langle p \rangle / B_{\phi 0}^2 = C_T I_p / a B_{\phi 0}$; 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 determined by stability considerations for each ARIES case. In the first stability region (FSR), C_T is a constant. In the second stability region (SSR), C_T is re-expressed in terms of $\epsilon\beta_s$, which is the relevant stability parameter for SSR, such that $C_T = C_q \epsilon\beta_s / 5q(1 - \epsilon^2)^2$; where $\epsilon \equiv A^{-1} = a/R_T$, β_s is the poloidal beta, q is the edge safety factor, and C_q is a constant determined through stability analysis.

The design requirements of the ARIES-III blanket and shield⁷ are relaxed because the D-³He fuel cycle reduces neutron activation and material damage by a factor of 10-20 relative to the D-T fuel cycle and eliminates the need for a tritium breeding blanket (³He is assumed to be available from lunar sources at 1 M\$/kg)⁸. An HT-9 shield that is 0.65 and 0.80 m thick inboard and outboard, respectively, captures the neutrons from D-T and D-D reactions for the thermal cycle and protects the advanced superconducting TF coils. An organic coolant is used in the reduced neutron environment to obtain a high thermal efficiency, $\eta_{TH} = 0.44$.

Because the fusion reactivity of the D-³He fuel cycle is low compared to that of the D-T fuel cycle, high beta that leads to high plasma current is needed to produce a net electric power of $P_E = 1$ GWe in a reasonably sized power plant. The fraction, f_{BC} , of the plasma current driven internally by the pressure-gradient-driven bootstrap effect must approach unity to obtain an economically attractive design. 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; a seed current must be driven on axis, and the overdrive in the plasma edge must be canceled. As a result of these current-density profile effects the fraction of the plasma current driven externally cannot vanish and is constrained to $|1 - f_{BC}| \geq 0.25$. The high temperature required to maximize the D-³He fusion power requires neutral beam injection (NBI) for current drive.

RESULTS

Two options were considered initially for ARIES-III: FSR and SSR. Reactor parameters for both options are given in Table I. Low bootstrap current-drive fractions ($f_{BC} \sim 0.5$) are typically predicted for the FSR. Synchrotron current drive ($f_{SC} = 0.35$) must supplement the bootstrap current drive ($f_{BC} = 0.43$) to sustain the high plasma currents ($I_p = 67.3$ MA) of the FSR. High efficiency ($\eta_{DC} = 0.8$) solid-state direct conversion of synchrotron power⁹ is also assumed for the FSR ARIES-III. To open an operating window in which the highly radiating ($f_{RAD} = 0.8$) D-³He plasma is maintained in power balance, $\tau_p/\tau_E \leq 1$ must be assumed, and high beta ($\beta = 0.1$) in the FSR is required; these constraints lead to low aspect ratio ($A = 3$). Even with these optimistic assumptions the FSR option has a significantly higher COE than the SSR option by ~ 20 mill/kWeh.

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TABLE I Comparison of Reactor Parameters for ARIES-I, ARIES-III, and a first stability region (FSR) variant of ARIES-III.

Parameter	ARIES-I	ARIES-III	FSR
Stability regime	FSR	SSR	FSR
Direct conversion	No	No	Yes
Fuel mix, ϕ_D/ϕ_T	0.5/0.5	0.5/0.0	0.7/0.0
Major toroidal radius, R_T (m)	6.75	7.5	6.45
Minor radius a (m)	1.5	2.5	2.15
Plasma elongation, κ	1.80	1.84	1.85
Plasma aspect ratio, $A = R_T/a$	4.5	3.0	3.0
Edge safety factor, q	4.5	6.85	2.75
Profile factors:			
density exponent, α_n	1.0	0.14	0.95
temperature exponent, α_T	1.1	0.79	0.55
normalized edge density, n_E/n	0.7	0.6	~ 0
Troyon coefficient, C_T	0.032	0.151	0.035
Plasma beta, β	0.019	0.24	0.10
Plasma poloidal beta, β_θ	2.80	5.41	0.93
Stability parameter, $\epsilon\beta_\theta$	0.62	1.80	0.31
Ion temperature, T_i (keV)	20	55	58
Electron temperature, T_e (keV)	19.1	53.3	53.4
Ion density, n_i ($10^{20}/\text{m}^3$)	1.25	2.08	1.91
Electron density, n_e ($10^{20}/\text{m}^3$)	1.47	3.27	2.65
Particle-to-energy confinement			
time ratio, τ_p/τ_E	4	2	1
Ion-to-electron energy confinement			
time ratio, τ_{Ei}/τ_{Ee}	1	1	1
Lawson parameter, $n_i\tau_E$ ($10^{20}\text{s}/\text{m}^3$)	2.9	24.5	24.4
Confinement multiplier over			
ITER-89P scaling ⁴ , H	2.6	7.2	3.7
Plasma gain, $Q_p = P_F/P_{CD}$	19.4	15.6	7.71
On-axis toroidal field, $B_{\phi 0}$ (T)	11.4	7.58	10.9
Field at TF coil, $B_{\phi c}$ (T)	21.4	14.0	20.9
Radiation fraction, f_{RAD}	0.49	0.72	0.80
Plasma current, I_p (MA)	10.3	29.9	67.3
Bootstrap-current fraction, f_{BC}	0.68	0.91 ^(b)	0.78 ^(a,b)
Current-drive efficiency (A/W)	0.033	0.043	0.059
Current-drive power to plasma, P_{CD} (MW)	100	172	285
Neutron wall loading (MW/m ²):			
14.1-MeV	2.5	0.06	0.16
2.5-MeV	~ 0	0.02	0.05
Thermal conversion efficiency, η_{TH}	0.49	0.44	0.44
Direct conversion efficiency, η_{DC}	NA	NA	0.8
Thermal power, P_{TH} (GWth)	2.55	3.00	1.95
Gross electrical power, P_{ET} (GWe)	1.25	1.32	1.49
Net electrical power, P_E (GWe)	1.0	1.0	1.0
Recirculating power fraction, $1/Q_E$	0.20	0.24	0.33
Mass power density, MPD (kWe/tonne)	84.7	90.1	57.9
Level of safety assurance ⁴ , LSA	2	1	1
Systems costs (M\$): ^(c)			
magnets	506	253	768
current drive	110	478	793
first wall and blanket	470	8	4
shield	196	174	111
Total direct cost, TDC (B\$) ^(c)	2.48	1.94	2.85
Total cost (B\$) ^(c)	4.78	3.63	5.33
Cost of electricity, COE (mill/kWeh) ^(c)	86.0	74.3	94.7

(a) Includes a fraction (0.35) of the current driven by synchrotron radiation

(b) The plasma current driven externally is constrained to be greater than 25% of the plasma current.

(c) All costs are reported in 1990 \$.

Because of the high $\epsilon\beta_\theta$, the SSR option relies on the bootstrap effect to drive plasma current internally. The magnitude of beta (C_T) required to provide a steady-state operating window for the SSR option, as determined

with the MakNTAU code, is shown in Fig. 1. For a more realistic assumption of $\tau_p/\tau_E = 2$, an operating window exists for SSR without auxiliary heating at $C_T \geq 0.15$. Using an ion temperature of $T_i = 55$ keV, which is near the fusion-power reactivity peak for D-³He, and $\tau_p/\tau_E = 2$, the A - α space was explored with the ASC, and the results are shown in Fig. 2. The curves in Fig. 2 display a shallow minimum in COE because recirculating power increases with smaller a , and mass ($\propto MPD^{-1}$) increases with larger a . Plasma power balance without auxiliary heating, which is too expensive to be considered, is not possible for $A > 3.05$. All of the cases in power balance are stable to ballooning modes, but require feedback stabilization of the kink modes. The $A = 3$ case then serves as a point of departure (POD) for parametric analysis of the ARIES-III option.

The restricted operating window available to SSR is expressed in Fig. 3 in physics, engineering, and economic terms, where COE -optimized perturbations in A , T_i , and τ_p/τ_E about the POD are displayed. As A is increased β decreases, which in turn requires larger, more massive (lower MPD) reactors with higher magnetic field and COE . The higher field increases synchrotron losses that must be offset by improved energy confinement (higher $n_i\tau_E$). The improved confinement increases the impurity fraction, which further degrades reactor performance. Eventually, $n_i\tau_E$ increases to a value beyond which plasma-power-balance solutions cannot be achieved without inordinate amounts of auxiliary heating power. In the temperature variation shown in Fig. 3, increased T_i ($\sim T_e$) increases both bremsstrahlung and synchrotron radiation that in turn require higher $n_i\tau_E$. The increased T_i also increases the NBI current-drive efficiency, as is evidenced by lower current drive power P_{CD} , and subsequently lowers COE . At lower T_i the fusion reactivity decreases, which requires higher $n_i\tau_E$. In the τ_p/τ_E variation shown in Fig. 3, increased τ_p/τ_E leads to better confined fusion products, which raises the impurity fraction, f_{IMP} . Higher f_{IMP} produces two effects: a) fuel dilution, which requires a more massive (lower MPD) reactor with higher plasma current that in turn results in higher COE , and b) higher required $n_i\tau_E$, which compensates for fuel dilution.

The off-optimum ARIES-III design choice is indicated in Fig. 2, and the associated design parameters are given in Table I. The ARIES-III design was selected by increasing a from the POD until the peak neutron wall loading fell below 0.1 MW/m² to reduce neutron activation and to achieve a level-of-safety-assurance rating of $LSA = 1$. For the ARIES-III design the peak neutron wall loading is 1.25 times the average wall loading reported in Table I. The LSA rating is not yet determined¹⁰; although the ARIES-III radiative inventory can be lethal if released off-site, release mechanisms that harness the significant magnetic (~ 165 GJ) and chemical ($\sim 6,000$ GJ) stored energy are not evident. If ARIES-III does not qualify for $LSA = 1$, an $LSA = 2$ rating results in $COE = 82.6$ mill/kWeh, which represents an 11% increase.

The benefit of SSR relative to FSR is reflected as reduced plasma current, magnetic field, and mass ($\propto MPD^{-1}$). More than just the design parameters for these two options must be examined, however; the physics assumptions and requirements must also be examined. For the FSR, energy must be confined as well as the ash particles are confined (i.e., $\tau_p/\tau_E = 1$) to maintain the D-³He plasma in a steady-state power balance. This assumption, if not physically impossible, would require some power-consuming mechanism (e.g. fishbone instabilities) to remove fusion products from the plasma at energies greater than the plasma temperature. Such a mechanism might also adversely impact the confinement of the bulk plasma. The $\tau_p/\tau_E = 2$ assumption allowed by invoking the SSR is more conservative than the $\tau_p/\tau_E = 1$ assumption used in the FSR. However, the $\tau_p/\tau_E = 2$ assumption in SSR remains optimistic relative to the conventional assumption of $\tau_p/\tau_E = 4$ used for ARIES-I. The SSR additionally requires energy confinement times that are seven times better than predicted by the ITER-89P scaling⁴. Both SSR and FSR stretch the physics assumptions to comparably extreme limits of credibility.

The preference for SSR over FSR for the ARIES-III design arises from the reduced plasma parameters previously mentioned (i.e., I_p , $B_{\phi 0}$, and MPD^{-1}) and the lower COE . A comparison of the ARIES-I and -III parameters given in Table I reveals that the lower power density of the D-³He fuel compared to D-T fuel requires ARIES-III to have three times the plasma current of ARIES-I ($I_p \approx 30$ and ≈ 10 MA, respectively). The ARIES-III higher beta results in an on-axis field that is two-thirds that used in ARIES-I ($B_{\phi 0} = 7.6$ and 11 T, respectively). Consequently, the magnets are the

Fig. 1. Contours of constant $C_T(\beta)$ for $Q_p = 16$ in an $n_i \tau_E - T_i$ space calculated by the MakNTAU code that indicates the minimum beta values required for the existence of a SSR operating window (i.e., power balance).

Fig. 2. Cost of electricity as a function of plasma minor radius for various aspect ratios calculated with the ASC. Also shown are the loci of COE minima, the point of departure (POD) for parametric analysis, and the ARIES-III design point.

Fig. 3. Sensitivity of ARIES-III design to variations in A , T_i , and τ_p/τ_E . Each point along a curve represents the COE optimum in minor radius, a . Also shown are the regions in which no power-balance solutions exist without auxiliary heating.

Fig. 4. Per cent change in the cost of electricity resulting from per cent changes about the POD in aspect ratio, A ; ion temperature, T_i ; ratio of particle-to-energy confinement time, τ_p/τ_E ; temperature-profile exponent, α_T ; net electric power, P_E ; current-drive efficiency, η_{CD} ; unscheduled maintenance time, t_u ; and unit cost of the NBI system, C_{NBI} .

Fig. 5. Change in the required ITER-89P confinement multiplier, H , produced by per cent changes about the POD in aspect ratio, A ; ion temperature, T_i ; ratio of particle-to-energy confinement time, τ_p/τ_E ; temperature-profile exponent, α_T ; net electric power, P_E ; current-drive efficiency, η_{CD} ; unscheduled maintenance time, t_u ; and unit cost of the NBI system, C_{NBI} .

dominant cost for ARIES-I, whereas the current-drive system is the dominant cost for ARIES-III. The higher beta of ARIES-III relative to ARIES-I ($\beta = 0.24$ versus 0.02, respectively) ultimately results in a lower COE for ARIES-III. Although the COE for ARIES-III is lower than that of either ARIES-I or FSR, the COE should be compared to fissile and fossil power plants that are projected to produce electricity in the range of 43-64 mill/kWeh in 1990 \$¹¹. Since the COE of ARIES-III is marginal by this comparison, a sensitivity of COE to perturbations in major design variables was undertaken to identify only high-leverage variables; these results are shown in Fig. 4. The eight variables examined weakly affect COE, except the net electric power, P_E . An $\sim 25\%$ increase in P_E produces the $\sim 10\%$ decrease in COE required to make ARIES-III economically competitive with fissile and fossil power plants. More substantial decreases of $\sim 50\%$ in the unscheduled maintenance time, t_u , and the unit cost of the neutral beam injectors, C_{NBI} , are required to decrease COE by $\sim 10\%$. Also of interest is the change in the design variables required to decrease the ITER-89P confinement multiplier to an acceptable value (i.e., $3 < H < 5$). From the results presented in Fig. 5, $H \sim 4$ can be achieved with changes of $\geq 100\%$ in the following variables: τ_p/τ_E , α_T , A , and P_E . Of these four variables only the following three can be changed to decrease COE and H simultaneously: τ_p/τ_E , A , and P_E . However, τ_p/τ_E is at the design limit, A is already small, and P_E is already near present-day utility limits.

SUMMARY

The ARIES team has completed the design of a tokamak reactor based on the D-³He fuel cycle to examine the consequences of a neutron-lean fuel cycle. A D-³He fuel cycle eliminates the need for a tritium breeding blanket that accounts for $\sim 40\%$ of the reactor plant equipment cost for the expensive ARIES-I SiC blanket and shield; the reduced neutron generation also allows the use of an organic coolant to obtain a high thermal efficiency $\eta_{TH} = 0.44$. Both first- and second-stability-region options were considered for ARIES-III. The second-stability-region design, based on limited experimental results, outperformed the first-stability-region design by a wide margin. Even with full cost credits for safety ($LSA = 1$ represents a 25 - 30% cost credit relative to $LSA = 4$), the SSR ARIES-III is only marginally competitive with median-experience fission power plants and is far from competitive with best-experience fission power plants¹¹. The application of the SSR physics to the D-T fuel cycle, however, is expected to produce an ARIES design that is competitive with fissile and fossil power plants. Generally, significant extrapolations beyond the present physics data base are required to burn D-³He fuel in tokamaks as presently understood or envisioned.

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