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Evolution of the ARIES-I Design in the ARIES and PULSAR Projects †

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ABSTRACT

After the completion of the ARIES-I study, the ARIES project generated additional tokamak conceptual designs with various levels of assumed advances in technology and physics and also updated models, ground rules, and designs of common subsystems. The ARIES-I design necessarily was updated repeatedly to incorporate the latest reactor advances and to obtain meaningful comparisons with subsequent designs in the ARIES and PULSAR series. The resulting series of ARIES-I designs are collected, and the underlying evolutionary changes are documented herein.

I. INTRODUCTION

The multi-institutional ARIES (Advanced Reactor Innovation and Evaluation Study) project generated a total of six conceptual tokamak power plant designs over the course of five and a half years. The first of these designs is the D-T fueled, steady-state ARIES-I [1] tokamak power plant that is based upon the conventional physics of the first stability regime (FSR), advanced superconducting technology (21 T at the TF coil), and a He-cooled, SiC blanket. After completing ARIES-I, physics and engineering models were updated; ground rules were changed; and better solutions to key engineering problems were realized. ARIES-I was updated repeatedly to include these changes and to obtain meaningful comparisons with the later designs, specifically those designs with a He-cooled, SiC blanket: the steady-state, second-stability-regime (SSR) ARIES-IV [2] and the pulsed, FSR PULSAR-I [3]. Consequently, a series of ARIES-I designs appears in both the published literature and in the ARIES reports, in which the Cost of Electricity (COE) has increased from 65 to 82 mill/kWeh, as a result of including these changes. The factors responsible for this increase in COE beyond inflation include: the introduction of Level of Safety Assurance (LSA) cost credits; redesigns of the blanket and shield to improve safety (*i.e.*, change the LSA rating) and to lower cost; imposition of a more severe constraint on the maximum allowed field at the TF coil (*i.e.*, $B_{\phi,c} \leq 16$ T); and reoptimization of the design at lower aspect ratio (from $A = 4.5$ to 4) and temperature (from $T_i = 20$ to 12 keV). This paper quantitatively documents the many changes that gave rise to the series of ARIES-I designs.

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II. DESIGN EVOLUTION

A. Original Design

A summary of ARIES-I parameters as they appear in the ARIES-I report [1] is given in Table I. The underlying philosophy of this first-stability design was to exploit advanced, high field ($B_{\phi,c} = 21$ T) TF coils for access to large aspect ratio ($A = 4.5$), which offers relatively high bootstrap-current fraction ($f_{BC} \sim 0.7$) and low plasma current (10 MA), current-drive power ($P_{CD} \leq 100$ MW), and recirculating power fraction ($\epsilon = 0.2$) that collectively yield high mass power density ($MPD \geq 100$ kWe/tonne).

B. Introduction of Safety Credits

During the six months between the completion of the ARIES-I report and the publication [4] of the updated ARIES-I (1990) given in Table I, the concept of safety credits and the LSA rating system were introduced with ramifications on more than just the COE. Enriched Zr was retroactively introduced to the ARIES-I breeder to reduce activation and to allow safety credits to be taken. However, the cost of enriched Zr (1,000 1992\$/kg), the use of more SiC composites rather than only cheaper bulk SiC (400 vs 70 1992\$/kg), and changes in some unit material costs and volumetric calculations combined to double the cost of the shield and the first wall, blanket, and reflector. Also included in the costs of ARIES-I (1990) is a 10% inflation rate spanning the period between 1988 and 1990. These changes resulted in a 7% increase in the direct cost of ARIES-I (1990) relative to ARIES-I (Table I). Per [5], the indirect costs were also increased from 69% to 93% of direct costs to conform with practices of the fission industry. The changes to direct and indirect costs together cause a 43% increase in the COE (*i.e.*, from 65 to 93 mill/kWeh). This updated ARIES-I (1990) design, which was isotopically enriched in ^{92}Zr to reduce radioactive inventory and release hazard, was determined to have an LSA=2 rating that reduces the COE from 93 to 81 mill/kWeh.

C. Plasma Model Updates

During the ARIES-III study [6], several models were refined that resulted in no net change in the COE, as is shown by the third column of Table I. These refinements include the introduction of the MakNTAU

TABLE I Parameter Evolution of the 1-GWe ARIES-I.

Parameter	ARIES-I [1]	ARIES-I (1990) [4]	ARIES-I (1992) [6]	ARIES-I (1992) [9]	ARIES-I (1994) [11]	ARIES-I (1994) [2,3,12,13]	ARIES-IA (1994) [2,3,12,13]
Plasma aspect ratio, $A = R_T/a_p$	4.5	4.5	4.5	4.5	4.5	4.0	4.0
Major toroidal radius, R_T (m)	6.75	6.75	6.75	6.75	7.64	6.17	7.40
Plasma minor radius, a_p (m)	1.50	1.50	1.50	1.50	1.70	1.54	1.85
Normalized beta, β_N (%)	3.20	3.20	3.20	3.20	3.20	3.20	3.20
Toroidal beta, β (%)	1.94	1.94	1.94	1.94	1.94	2.26	2.26
Ion temperature, T_i (keV)	20.0	20.0	20.0	20.0	20.0	12.0	12.0
Electron temperature, T_e (keV)	19.3	19.3	19.4	18.9	19.0	13.0	13.0
Ion density, n_i ($10^{20}/\text{m}^3$)	1.24	1.24	1.23	1.29	1.07	1.73	1.31
Electron density, n_e ($10^{20}/\text{m}^3$)	1.45	1.45	1.43	1.56	1.26	1.92	1.46
Lawson parameter, $n_i\tau_E$ ($10^{20}\text{s}/\text{m}^3$)	2.90	2.90	2.7	4.1	3.11	1.70	1.72
ITER-89P scaling [9] multiplier, H	2.59	2.59	2.6	3.7	2.69	1.76	1.80
Radiation fraction, f_{RAD}	0.50	0.50	0.47	0.48	0.50	0.18	0.18
Plasma current, I_p (MA)	10.2	10.2	9.5	9.7	10.9	10.5	10.9
Bootstrap-current fraction, f_{BC}	0.68	0.68	0.68	0.68	0.68	0.65	0.65
CD efficiency, γ (10^{19} A/W m^2)	3.30	3.30	3.30	3.30	2.92	2.16	2.16
CD efficiency, I_p/P_{CD} (mA/W)	34	34	34	33.2	30.3	18.2	20.0
CD power to plasma, P_{CD} (MW)	96.7	97.2	89	99	115	202.5	192.7
On-axis toroidal field, $B_{\phi 0}$ (T)	11.3	11.3	10.6	10.7	10.6	9.64	8.39
Coil grade, n_j	6	6	6	6	7	7	5
Field at TF coil, $B_{\phi c}$ (T)	21.0	21.3	19.9	20.1	19.1	19.8	16.0
TF-coil current density, j_{TF} (MA/ m^2)	28.4	27.8		28.2	24.5	24.3	26.7
TF-coil unit cost, c_{TF} (\$/kg)	89.2	97.7	97.7	103.0	97.8	97.8	92.7
Average neutron load, I_w (MW/ m^2)	2.48	2.48	2.5	2.2	2.06	2.99	2.10
First-wall/blanket life, $I_w\tau$ (MW yr/ m^2)	20.0	20.0	20.0	13.0	13.0	13.0	13.
Blanket energy multiplication, M_N	1.30	1.30	1.30	1.30	1.23	1.23	1.23
Thermal conversion efficiency, η_{TH}	0.49	0.49	0.49	0.49	0.49	0.49	0.49
Recirculating power fraction, ϵ	0.20	0.20	0.19	0.20	0.21	0.29	0.28
Masses (ktonne):							
first wall, blanket, and reflector	1.13	1.44		1.55	0.50	0.42	0.57
shield	1.82	1.82		1.95	4.63	3.67	5.08
TF coils	2.93	3.04		3.07	4.18	3.50	3.80
PF coils	1.82	0.72		2.03	0.93	0.86	1.02
fusion power core	10.1	9.02		11.2	13.9	11.4	14.3
Mass power density, MPD (kWe/tonne)	99.0	110.9	101.2	89.3	71.7	87.4	70.2
Level of Safety Assurance, LSA	NA	2	2	2	1	1	1
Dollar year	1988	1990	1990	1992	1992	1992	1992
Reactor plant equipment costs (M\$):							
first wall, blanket, and reflector	260.3	489.9	476	383.4	104.5	88.3	120.4
shield	77.3	203.8	196	201.9	515.7	413.0	570.6
magnets	392.3	339.1	366	458.0	436.7	371.5	392.2
current-drive/heating systems	103.9	108.0	98	155.0	155.2	236.5	227.3
Total direct cost, TDC (B\$)	2.14	2.29	2.31	2.47	2.35	2.27	2.52
Total capital cost, TDC (B\$)	3.62	4.41	4.45	4.76	4.40	4.24	4.70
Cost of electricity (mill/kWeh):							
capital return	52.56	64.09	64.71	69.07	63.8	61.59	68.29
O&M	6.67	5.54	8.68	9.16	7.5	7.54	7.54
blanket replacement	5.58	10.93	6.73	15.20	5.0	6.75	6.00
decommissioning	0.50	0.50	0.50	0.50	0.25	0.25	0.25
fuel	0.04	0.03	0.03	0.03	0.03	0.03	0.03
total COE		81.10	81	93.96	76.6	76.17	82.11
total COE w/o safety credits (LSA=4)	65.34		93	107.04	101	100.63	108.08

[7] plasma power balance model that directly affects fuel pressure and indirectly plasma current and field. At the time of ARIES-III, a practice was initiated of reporting the COE with and without safety credits. An LSA=2 rating reduces the COE by 13% relative to no safety credits.

D. Fluence-Life Reduction

Between the ARIES-III [6] and ARIES-II/IV [2] studies, the neutron fluence life for SiC composite was reduced from 20 to 13 MW yr/m². Consequently, the blanket replacement component of the COE for ARIES-I (1992) [8] doubled, as is indicated in Table I. Additionally, the current-drive model was refined, and adjustments in some unit costs were included in the costs reported. This combination raised the ARIES-I COE to 94 and 107 mill/kWeh with and without safety credits.

E. Blanket and Shield Redesign

The ARIES-I update reported in [10] and given in fifth column of Table I benefits from several developments that occurred during the ARIES-II/IV study [2] described below. New SiC blanket and shield designs were developed for ARIES-IV [2] that moved that portion of the reflector that could survive for the full life of the plant into the permanent shield to reduce the blanket-replacement cost; the blanket replacement component of the COE was reduced by nearly a factor of four. A second important blanket change was to replace the Li₂ZrO₃ breeder with Li₂O to improve the LSA rating from 2 to 1, which decreases the COE by ~ 10%, and reduces the unit cost of the shield. The resulting blanket and shield are thinner than the original ARIES-I blanket and shield (1.31 *versus* 1.39 m inboard and 1.74 *versus* 1.79 m outboard). Because the blanket energy multiplication, M_N , was inadvertently reduced from 1.3 to 1.23, the plasma size (*i.e.*, a_p and R_T) was necessarily increased to maintain constant net electrical output. The new blanket and shield were retrofitted to subsequent ARIES-I updates. Also during the ARIES-II/IV study, the available TF-coil conductor types were redefined so that near-term, advanced, and super-advanced coil technologies are now represented by coil grades $n_j = 5, 7$, and 8 that correspond to limits on the peak field at the TF coil of $B_{\phi c} \leq 16$ T, ≤ 21 T, and > 21 T, respectively. In addition to differences in current-density scalings with field [2], the unit costs of each coil grade were differentiated by ~ 5%, with the most advanced coil grade having the most expensive unit cost (*i.e.*, 92.7, 97.8, and 103.0 \$/kg, respectively). Of these three coil grades, the advanced, $n_j = 7$ coil grade was adopted for subsequent ARIES-I updates. The original ARIES-I vertical maintenance scheme was also re-examined during the ARIES-II/IV

study and judged significantly less credible than horizontal maintenance. Consequently, a horizontal maintenance scheme was developed for ARIES-II/IV that required the TF-coil outer leg be moved radially outward to provide clearance for the horizontal maintenance scheme. The application of this maintenance scheme to ARIES-I updates increases the COE by ~ 5%, mainly because of increased magnet cost. Also initiated at this time is a switching from a previous practice of fixing numbers such as the bootstrap-current fraction, f_{BC} , and the current-drive efficiency, γ , at values originally used in ARIES-I to using the appropriate physics models. Consequently, the current-drive power increased by ~ 10%, and a further increase in size was required to maintain constant net electrical power. In addition to the above changes, a 5% inflation rate for the period from 1990 to 1992, minor adjustments to unit costs, and a reduction in the indirect costs are included in the COE in [10] and in the fifth column of Table I. Because of the high relative cost of the magnets, this update no longer operates at the maximum allowable field. This update represents a significant shift from the original ARIES-I design.

F. Adoption of Gaseous Divertor

Additional modifications to the ARIES-I design were incorporated into the update appearing in the ARIES-II/IV report [2], in [3,12,13], and in Table I to place ARIES-I on a common ground with the ARIES-II and -IV designs. A highly recycling divertor was used in ARIES-I that requires high edge-plasma densities and a high plasma temperature to assure divertor longevity by radiating half of the fusion alpha-particle power to the first wall. A gaseous divertor was adopted for the ARIES-II and -IV designs and was retrofitted to ARIES-I. The gaseous divertor, as implemented herein, places no constraint on either plasma temperature or radiation fraction, although the understanding of how this happens is incomplete. Without a temperature constraint, the design optimizes the COE at a lower plasma temperature that increases the fusion power density and permits a smaller FPC size for the same net electrical power. Other benefits that accompany decreased T_i include a significant reduction in the confinement multiplier, H . However, the decreased electron temperature decreases the current-drive efficiency ($\gamma \propto \bar{T}_e^{0.77}$, where $\bar{T}_e$ is the volume averaged electron temperature) and, combined with increased electron density, nearly doubles the current-drive power ($\gamma \propto n_e$). The increased MPD accompanying the reduced size and the associated cost savings are sufficient to overcome the increased cost associated with the increased recirculating power fraction that is a consequence of increased P_{CD} . In addition, the higher MPD system that results at lower plasma temperature, which is a direct consequence of the gaseous divertor,

optimizes the COE at $A = 3.5$. As with ARIES-II/IV, which optimized the COE at $A = 3.2$, the aspect ratio is limited to $A \geq 4$ to improve the layout, accessibility, and maintainability of the FPC with little impact on the COE. This aspect-ratio dependency is in contrast to that displayed by the original ARIES-I design, which optimized the COE at a large aspect ratio ($A = 4.5$) to increase the bootstrap-current fraction at the expense of plasma beta, β , because of the availability of relatively cheap, high-field TF coils.

G. Reduced-Field TF Coils

To further facilitate a common-ground comparison of first (*i.e.*, ARIES-I) and second (*i.e.*, ARIES-IV) stability regimes, the ARIES-I coil grade was made the same as that of the ARIES-II/IV designs, which use the least advanced, cheapest $n_j = 5$ coils. Optimization of such a design, subject to the constraint that $A \geq 4$, results in the update reported in [2,3,12,13] and given in Table I. This ARIES-I update is appropriate for judging the cost differential between first and second stability regimes; a first-stability tokamak power plant is projected to produce electricity 21% more expensively than a second-stability tokamak power plant. A 16-T update of ARIES-I will represent the first stability regime in a comparison of tokamak confinement schemes to determine the preferred scheme for use in the US Demo Power Plant [14,16].

III. SUMMARY

The ARIES-I design has been repeatedly updated in response to developments within the power-plant design community and to criticisms of the original design (*e.g.*, the credibility of vertical maintenance). The introduction of safety credits has had a large impact on the ARIES-I updates. In an effort to obtain a better LSA safety rating and lower COE, the ARIES-IV blanket and shield have been adopted. Also design optimism has been tempered in some areas, as is evident by, for example, adoption of a reduced fluence limit, increased cost for more advanced TF coils, and a reduced maximum allowable field at the TF coil. The adoption of the gaseous divertor with no impact on the plasma acknowledges the lack of a credible divertor solution. These changes have been responsible for the evolution of the ARIES-I updates away from the original ARIES-I design philosophy of optimizing the COE at large aspect ratio to increase the bootstrap-current fraction and decrease current-drive power at the expense of plasma beta, β . The continued design efforts of the ARIES team will result in further ARIES-I updates.

REFERENCES

- [1] F. Najmabadi, *et al.*, "The ARIES-I Tokamak Reactor Study," University of California Los Angeles report UCLA-PPG-1323 (1991).
- [2] F. Najmabadi, *et al.*, "The ARIES-II and -IV Second Stability Tokamak Reactors," University of California Los Angeles report UCLA-PPG-1461 (to be published).
- [3] F. Najmabadi, *et al.*, "The PULSAR Tokamak Reactor Study," University of California San Diego report (to be published).
- [4] R. L. Miller, R. A. Krakowski, and the ARIES Research Team, "Options and Optimizations for Tokamak Reactors: AIRES," *Fus. Technol.* 19 (May 1991) 802.
- [5] J. G. Delene, "Updated Comparison of Economics of Fusion Reactors with Advanced Fission Reactors," *Fus. Technol.* 19 (May 1991) 807.
- [6] F. Najmabadi, *et al.*, "The ARIES-III D-³He Tokamak Reactor Study," University of California Los Angeles report UCLA-PPG-1384 (to be published).
- [7] K. A. Werley, "Reversed Field Pinch Ignition Physics," Los Alamos National Laboratory document LA-UR-89-4093 (1989).
- [8] C. G. Bathke and the ARIES Research Team, "A Systems Analysis of the ARIES Tokamak Reactors," *Fus. Technol.* 1992, 2 (1992) 1658.
- [9] D. E. Post, K. Borrass, J. D. Callen, S. A. Cohen, J. G. Cordey, F. Engelmann, *et al.*, "ITER Physics," International Thermonuclear Experimental Reactor documentation series No. 21 (November 1990).
- [10] R. A. Krakowski, C. G. Bathke, R. L. Miller, K. A. Werley, "Lessons Learned from the Tokamak Advanced Reactor Innovation and Evaluation Study (ARIES)," Los Alamos National Laboratory report LA-UR-93-4217 (December 8, 1993).
- [11] R. A. Krakowski, C. G. Bathke, R. L. Miller, and K. A. Werley, "Lessons Learned from the Tokamak Advanced Reactor Innovation and Evaluation Study (ARIES)," *Fus. Technol.* 26(3), 1111 (November, 1994).
- [12] C. G. Bathke and the ARIES Research Team, "A Comparison of Steady-State ARIES and Pulsed PULSAR Tokamak Power Plants," *Fus. Technol.* 26(3), (November 1994) 1163.
- [13] C. G. Bathke and the ARIES Research Team, "A Comparison of Steady-State and Pulsed Tokamak Power Plants," *Fus. Technol.* 1994, 2 (1994) 1509.
- [14] C. G. Bathke and the ARIES Research Team, "A Preliminary Systems Assessment of the Starlite Demo Candidates," this conference.
- [15] F. Najmabadi, L. Waganer, and the ARIES Research Team, "The Starlite Project: The Mission of the Fusion Demo and Preliminary Assessment of Demo Candidates," this conference.