SYSTEMS CONTEXT OF THE ARIES-AT CONCEPTUAL FUSION POWER PLANT

Ronald L. Miller and the ARIES Team
University of California San Diego
9500 Gilman Drive
La Jolla, CA 92093-0417 USA
(858)534-7842

ABSTRACT

A 1-GWe-class magnetic fusion power plant conceptual design emphasizing advanced tokamak physics and advanced technologies is designated ARIES-AT. The point design and accessible operating space is described. Key trades and sensitivities are presented to illuminate the drivers of both direct cost and cost of electricity (COE).

I. INTRODUCTION

The multi-institutional ARIES Team has considered the conceptual design of a 1-GWe-class deuterium-tritium (DT)-fueled tokamak power plant, emphasizing advanced-tokamak physics and advanced technologies, designated ARIES-AT[1]. The ARIES-AT provides a comprehensive integration of plasma physics, engineering, and cost projections [with emphasis on the fusion power core (FPC)] to assess the economic, environmental, and safety attributes of the AT approach. Using a previous study, ARIES-RS[2], as a point of departure, it is possible to characterize the contributors to overall performance improvement. At this level of consideration, the compatibility and interaction of new understanding or innovations combine to yield incremental improvements to the projected performance of the concept.

It is also useful to expose the broader context of the accessible operating space in light of new influences that might challenge the traditional guidance and assumptions of these recent tokamak power plant studies with a view toward setting the direction of additional studies. These influences include the changing regulatory climate in the electricity sector and the resultant impacts on customer (*i.e.*, both power generating entity and the general public as retail consumer) requirements.

II. PHYSICS ASPECTS

ARIES-AT operates at a plasma aspect ratio ($A \equiv$ plasma major toroidal radius, R_T, divided by the plasma half-width, a_p, at the midplane) taken to be near 4.0, representing a compromise between maximizing the plasma beta (the ratio of plasma pressure to confining magnetic-field pressure) and the desire to reduce the poloidal peaking of the first-wall neutron load and provide maintenance access. The beta of the ARIES-AT is higher than that of the ARIES-RS, which also had $A = 4.0$, largely because of increased plasma elongation, κ. Three physics cases are summarized in Table I, representing a range of normalized betas, β_N. The plasma beta and normalized beta are related by the expression, $\beta = \beta_N(I_p/a_pB_T)$, where I_p is the plasma current, and B_T is the toroidal magnetic-field strength on axis. The plasma density at the plasma edge (separatrix) is related to the average density by the ratio, n_s/n, and the ratio of the separatrix density to the central density, $n(0) \equiv n_0$, is $n_s/n_0 = 0.20$ for all three cases.

Operation away from the theoretical beta limit provides a margin intended to reduce the probability of plasma disruptions; this margin is expressed as a percentage (90%) of the limit. Plasma radial density and temperature profiles are tuned to improve the alignment of the bootstrap current-density profile so as to maximize the stable beta and bootstrap-current fraction, f_{BC}. When Case B is adjusted for the disruption-avoidance margin, such that $\beta_n = 0.604 \rightarrow 0.54$, the value of f_{BC} drops to $\sim$ 0.91, it should be noted.

Table I. ARIES-AT Extrapolated Physics Basis*.

Case:	A	B‡	C
β_N	5.59	6.04	6.81
κ	2.14	2.14	2.14
δ	0.78	0.78	0.78
β (%)	9.34	10.17	11.76
$\beta^\dagger$ (%)	8.40	9.15	10.59
β_p	2.10	1.90	2.47
n_s/n°	0.28	0.27	0.24
f_{BC}	0.941	0.945	0.908
Safety factor, $q(0)$	3.69	3.56	3.56
Safety factor, $q(a)$	3.97	4.05	3.94

* $A \equiv R_T/a_p = 4.0$
‡ Baseline ARIES-AT design
† Anti-disruption margin (0.9)
° Assumes $n_s/n_0 = 0.20$

Steady-state operation (after a start-up heating transient to near ignition) is provided by radiofrequency (rf) systems to provide current-drive (CD) and plasma profile control; the absorbed power is ~ 37 MW. The plasma temperature optimizes near 18 keV. Neutral-beam injection (NBI) was considered as a back-up system, which could also be used to drive plasma rotation as a potential stabilizing technique. Energy confinement is monitored by several empirical scaling relationships expressing the energy confinement time, τ_E, as a function of device parameters. Addition of impurities (*e.g.*, Ar) increases the plasma core radiation fraction f_{RAD}, to about 0.30 at the cost of higher effective plasma charge, $Z_{eff} \simeq 1.8$, and a higher Lawson confinement parameter, $n\tau_E$.

III. ENGINEERING ASPECTS

If the plasma transport power crossing the separatrix can be redistributed uniformly over the divertor-plate area by local radiation, the load is a modest 2 MW/m^2 for the double-null ARIES-AT configuration. The peak divertor surface load is ~ 5 MW/m^2; the inboard first-wall sees ~ 1 MW/m^2.

An advantage made possible by high-β operation is lower magnetic-field strength (for a nominal power level and FPC size), which translates into reduced coil forces and stresses. The ARIES-AT study also considered the use of high temperature superconductor (HTS) toroidal-field coils (TFCs), in contrast to low temperature superconductors (*e.g.*, Nb_3Sn). One advantage projected[3] for the HTS technology is lower (by about half) unit cost (~ 50 $/kg) due to advanced manufacturing techniques.

The first-wall/blanket/divertor structural material (under development) is low-activation SiC$_f$/SiC composite[4] with a unit cost of 400 $/kg. The structural neutron-damage fluence lifetime, $\tau_{max} = 18.5\,MWa/m^2$, represents a SiC burnup rate of 0.77% per full power year (FPY). This material enables high temperature operation in a Brayton power-cycle system[5] with high efficiency, $\eta_{TH} = 0.59$. No cost adders have been included in the standard cost scalings to offset the improvement in efficiency. The large increase in thermal-conversion efficiency reduces the level of fusion power to meet the target net electrical power output, and correspondingly reduces the first-wall and divertor loads.

The coolant is a Pb-17Li eutectic (enriched to 90% ^{6}Li), which also provides tritium-breeding[6]. The neutron energy multiplication in the ARIES-AT is $M_N = 1.1$, similar to many designs.

Maintenance access exists between the outer legs of the 16 TF coils (after draining the PbLi from the blanket sectors and breaking coolant and electrical connections) through large ports. Rapid changeout of the integrated nuclear and plasma-facing FPC components maximizes the operating time, with maintenace and test operations largely being performed off-line[7].

IV. DESIGN-POINT DETERMINATION

The ARIES-AT target power output, $P_E = 1,000\,MWe(net)$, is consistent with previous ARIES designs. This unit size roughly corresponds to the present U.S. fission-plant fleet average, with the youngest plants tending to be larger (up to ~ 1,250 MWe). The largest, recent fission plants in France are at ~ 1,450 MWe. It may be noted that STARFIRE[8] was sized at 1,200 MWe. The dependence of COE on average neutron wall load, I_w (MW/m^2), is shown in Fig. 1 for various power outputs and FPC sizes.

Using the ARIES-RS[2] as a point of departure, the improvements leading to lower COE values (77 $\rightarrow$ ~ 52 mill/kWeh) for the ARIES-AT may be allocated as follows: about 1/3 for combined physics and engineering changes in the FPC, about 1/3 for power cycle efficiency improvements, which reflect

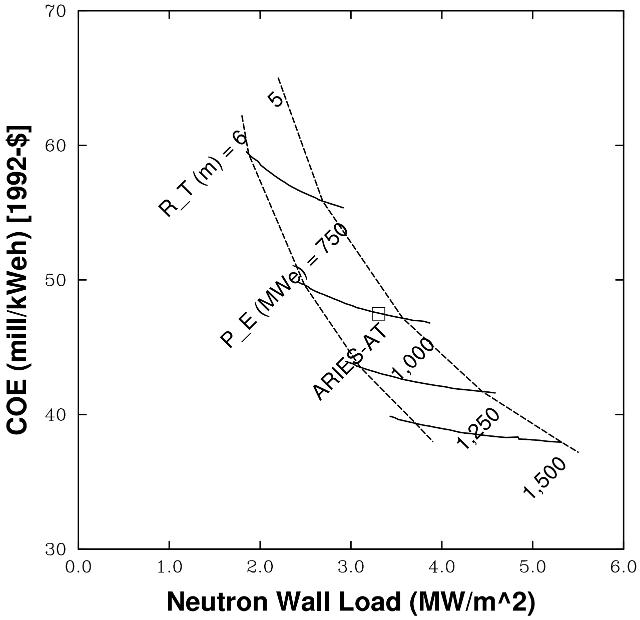

Figure 1. Dependence of ARIES-AT projected Cost of Electricity (COE) on average neutron wall load, I_w (MW/m^2), for various values of net output power, P_E. Isoquants for representative values of major toroidal radius, R_T, at fixed plasma aspect ratio, $A \equiv R_T/a_p = 4.0$, are shown as dashed lines. Plant capacity factor, $p_f = 0.85$, is fixed, and $LSA = 1$.

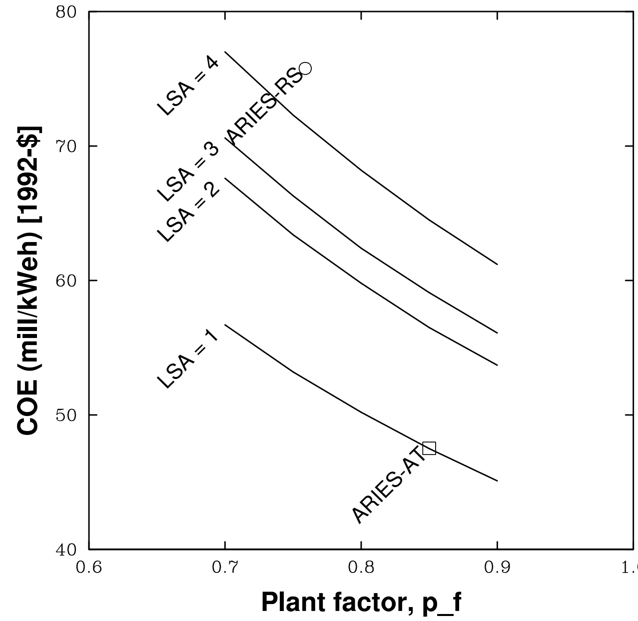

Figure 2. Dependence of ARIES-AT projected Cost of Electricity (COE) on plant capacity factor, p_f, for various LSA values. Also at 1,000 MWe, ARIES-RS[2], with $\eta_{TH} = 0.49$, had $LSA = 2$.

back on the FPC, and about 1/3 for the change from LSA = 2 to LSA = 1. Up to this point, the common study groundrules hold. Finally, the assumption of a higher plant factor ($p_f \simeq 0.76 \rightarrow 0.85$) gains the reference COE $\simeq$ 47 mill/kWeh [1992-$].

COE results assuming the plant capacity factor, $p_f \simeq 0.76$, following STARFIRE[8] and previous ARIES studies, are reported. A more optimistic value of 0.85 is now considered, as well. The plant capacity factor reflects forced and scheduled outages. The dependence of COE on plant capacity factor, p_f, is shown in Fig. 2.

The ESECOM group[9] developed the concept of Level of Safety Assurance (LSA) as a quantitative credit for savings resulting from the incorporation of passive safety features, or "reducing the nuclear envelope". These credits, appropriate for a conceptual design, rather than for "bottoms-up" cost estimates were adopted for ARIES work at the time of the ARIES-II/IV studies. LSA = 4 represents full nuclear-safety-grade construction methods and documentation, while LSA = 1 represents the limit of conventional power plants. It remains arguable whether any DT fusion plant can achieve LSA = 1.

Parameters for the 1,000 MWe ARIES-ST design point are summarized in Table II. Costs are reported using the same groundrules as used for previous ARIES studies using 1992 constant U.S. dollars to facilitate comparisons, although an update and rework of these assumptions is in progress, following Ref. 10. The construction lead time is assumed to be a nominal six years, as for STARFIRE[8], in setting the time-related (interest during construction) costs. This assumption was considered to be optimistic twenty years ago in light of the prevailing (U.S.) fission experience. The scheduled replacement of blanket/shield/CP components subject to a fluence lifetime contributes about 10% of the COE and is comparable to the nominal operation and maintenance (O&M) expenses also projected for a fission plant of this size.

VI. REVISITING THE ASSUMPTIONS

It is generally granted that magnetic fusion systems could benefit from economies of scale, as has been (re)considered in the context of combined electricity generation and hydrogen production at the 4-GWe level[11], taking into account appropriate additional costs for spinning reserve. Pushing the ARIES-AT in this direction lowers the COE, as shown in Table III, but detailed engineering designs of larger systems have not been made.

Table II. 1-Unit 1-GWe(net) ARIES-AT Parameters.

Plasma aspect ratio, $A = R_T/a_p$	4.0
Major toroidal radius, R_T (m)	5.20
Plasma minor radius, a_p (m)	1.30
Plasma elongation, κ_x	2.18
Plasma triangularity, δ_x	0.84
Circularized safety factor, q_*	2.09
Stability parameter, $\epsilon\beta_p$	0.57
Normalized beta, β_N (%mT/MA)†	5.40
Toroidal beta, β (%)†	9.2
Poloidal beta, $\beta_p{}^\dagger$	2.28
Ion temperature, T_i (keV)	18.0
Electron temperature, T_e (keV)	18.1
Ion density, n_i (10^{20}/m^3)	1.71
Electron density, n_e (10^{20}/m^3)	2.15
Lawson parameter, $n_i\tau_E$ (10^{20}s/m^3)	3.42
ITER-89P scaling multiplier, H_{89}	2.65
IPB98(y) scaling multiplier, H_{98}	1.37
Plasma core radiation fraction, f_{RAD}	0.30
Plasma current, I_p (MA)	12.8
Bootstrap-current fraction, f_{BC}	0.915
CD efficiency, γ_B (10^{20} A/W m^2)	4.16
CD power to plasma, P_{CD} (MW)	34.6
On-axis toroidal field, B_T (T)	5.86
Peak field at TF coil, B_{TF} (T)	11.1
Tor./pol. stored magnetic energy, W_B (GJ)	38/7
TF-coil current density, j_{TF} (MA/m^2):	67
Peak FW neutron load, $\hat{I}_w$ (MW/m^2)	4.94
Avg. FW neutron load, I_w (MW/m^2)	3.29
First-wall/blanket life, $I_w\tau$ (MWa/m^2)	18.5
Norm. divertor heat flux, P_{TR}/R_T (MW/m)	52.7
Blanket energy multiplication, M_N	1.1
Thermal conversion efficiency, η_{TH}	0.59
Recirculating power fraction, $\epsilon(=1/Q_E)$	0.15
Mass power density, MPD (kWe/tonne)	191
Thermal power, $P_{TH}(MWt)$	1,982
Gross electric power $P_{ET}(MWe)$	1,169
Net electric power output $P_E(MWe)$	1,000
Net plant efficiency, $\eta_p = \eta_{TH}(1-\epsilon)$	0.50
Total direct cost, TDC (B$)	1.52
Unit direct cost, UDC ($/kWe)	1,521
Total capital cost, TCC (B$)	2.84
Plant factor, p_f	0.76/0.85
Cost of electricity (mill/kWeh, 1992-$):	
total COE w/ safety credits (LSA=1)	52/47.5
total COE w/ safety credits (LSA=2)	63/56.6
total COE w/ safety credits (LSA=3)	65/59.2
total COE w/o safety credits (LSA=4)	71/64.6

† Includes disruption-avoidance margin (0.9).

Table III. ARIES-AT Economy of Scale*.

p_f / P_E (MWe):	1,000	1,500	2,000	2,500
0.76†	52.5	44.2	40.7	36.6
0.85	47.3‡	39.9	36.7	32.8

* COE (mill/kWeh) [1992-$] with LSA = 1. † *cf.* Refs. 2, 8. ‡ ARIES-AT baseline.

About a decade ago, fission-plant designers moved to smaller plants as they explored passive safety features at lower power density. The latest version of the 600-MWe AP600[12] invokes modular construction techniques to reduce the construction lead time from four to three years. Simplifications attributed to passive safety are generally consistent with the LSA overlay. Reductions of 15% in O&M costs from present experience are assumed. The latest version also exploits the 2-units per site assumption to achieve COE reductions to 41 mill/kWeh, which is thought to be noncompetitive in the U.S. market. As a sidebar[12], a 1,000-MWe version, again with 2-units per site, uses the fission economy of scale to reach $\sim$ 30 mill/kWeh. Historically, the upward ratcheting of fission plant sizes before Nth-of-a-kind cost savings could be realized, was one of the contributing factors to the disenchantment with fission. Safety and radioactive waste issues were also very important. Any orders of such plants of either size in the U.S. would break a twenty-year drought. Plant factors approaching 90% are assumed, but that level is already in the reach of the better performers of the U.S. fleet in recent years[13,14].

Coal plant projections[14] (1998 dollars) decline from 41 mill/kWeh in 2005 to 39 mill/kWeh in 2020 as efficiencies improve. Similarly, natural-gas-plant projections[15] (not corrected for the recent jump in fuel prices) are 35 mill/kWeh in 2005 and 37 mill/kWeh in 2020. The consideration of carbon management costs[16], calibrated at 10 $/ton adds $\sim$ 2 mill/kWeh to the coal projection and $\sim$ 1 mill/kWeh to the natural gas value.

It has always been possible to contemplate multiple units at the same site, but these issues have not been treated explicitly. Such units are largely independent of each other, but could share some personnel to achieve O&M savings. A recent version of the Japanese A-SSTR[17] invokes, in principle, the

2-unit per site assumption. A set of n-unit credits is available[18] and should be calculated for fusion applications.

A learning-curve credit applied to the FPC, again dating from STARFIRE[8], uses an across-the-board progress ratio of 80% to represent savings for each doubling of production up to the 10th-of-a-kind plant; this credit should be revisited and differentially applied to each subsystem as more information emerges.

VII. CONCLUSIONS

Key physics and engineering trade-offs and constraints leading to the selection of a representative ARIES-AT power-plant conceptual design point have been examined. The ARIES-AT benefits from the invocation of both physics and technology extrapolated improvements. Some additional benefits derive from the consideration of modifications to financial and other assumptions, which represent departures from the historic ARIES basis, but are useful in making timely comparisons with the competing technologies. There may indeed be unavoidable reasons why a complex fusion plant cannot be expected to achieve the plant factors of the best competitors or that fusion plants will take longer to construct. The payoff in revisiting these issues justifies the effort. At the risk of producing a torrent of COE numbers for the many combinations of soft parameters, this parametric work does not interfere with the engineering optimization of the basic fusion FPC.

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REFERENCES

1. F. Najmabadi, *et al.*, "Impact of Advanced Technologies on Fusion Power Plant Characteristics: The ARIES-AT Study," these proceedings.
2. Special Issue: ARIES-RS Tokamak Power Plant Design, *Fus. Eng. and Design*, 38, Nos. 1,2 (1997).
3. L. Bromberg, *et al.*, "Options for the Use of High Temperature Superconductor in Tokamak Fusion Reactor Designs," *Fus. Eng. and Design*, 52 [to be published].
4. A. R. Raffray, *et al.*, "ARIES-AT Blanket and Divertor," these proceedings.
5. R. Schleicher, A. R. Raffray, and C. P. C. Wong, "An Assessment of the Brayton Cycle for High Performance Power Plant," these proceedings.
6. L. El-Guebaly, "Nuclear Performance Assessment for the ARIES-AT Power Plant," these proceedings.
7. L. M. Waganer, "Comparing Maintenance Approaches for Tokamak Fusion Power Plants," these proceedings.
8. C. C. Baker, *et al.*, "STARFIRE–A Commercial Tokamak Fusion Power Plant Study," Argonne National Lab. report ANL/FPP-80-1 (1980).
9. J. P. Holdren, *et al.*, "Report of the Senior Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy," Lawrence Livermore National Laboratory report UCRL-53766 (Sep. 1989).
10. J. G. Delene, *et al.*, "An Assessment of the Economics of Future Electric Power Generation Options and the Implications for Fusion– Revision 1," Oak Ridge National Laboratory report ORNL/TM-1999/243/R1 (Feb. 2000).
11. J. Sheffield, *et al.*, "A Study of Options for the Deployment of Large Fusion Power Plants," Joint Institute for Energy & Environment report JIEE 2000-06 (June 2000).
12. J. W. Winters, "The AP600–Design Certified and Ready to Build," *Nuclear News*, 43, 10 (Sep. 2000) 36. [also www.ap600.westinghouse.com]
13. Energy Information Administration, "Annual Energy Review 1999," US Dept. of Energy report DOE/EIA-0384(99) (July 2000).
14. L. C. Cadwallader and D. A. Petti, "A Review of Availability Growth in Energy Production Technologies," Proc. 18th IEEE/NPSS Symposium on Fusion Engineering, 99CH37050, (Oct. 1999) 585.
15. Energy Information Administration, "Annual Energy Outlook 2000 With Projections Through 2020," US Dept. of Energy report DOE/EIA-0383(2000) (Dec. 1999).
16. US Department of Energy, " Energy Department Selects Eight of Its National Labs to Conduct Research Into Greenhouse Gases," press release R-00-055 (March 2, 2000).
17. M. Kikuchi, Y. Seki, and K. Nakagawa, "The Advanced SSTR," *Fus. Eng. and Design*, 48, Nos. 3,4 (Sep. 2000) 265.
18. J. G. Delene and C. R. Hudson II, "Cost Estimate Guidelines for Advanced Nuclear Power Plants," Oak Ridge National Laboratory report ORNL/TM-10071/R3 (May 1993).