

Impact of Advanced Physics and Technology on the Attractiveness of Tokamak Fusion Power Plants

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Abstract--During the past ten years, the ARIES Team has studied a variety of tokamak power plants with different degrees of extrapolation in plasma physics and technology from present database. Continuation of research has allowed us to apply lessons learned from each ARIES design to the next. The results of ARIES tokamak power plant studies provide a large body of data that highlight the tradeoffs and relative leverage of advanced plasma physics and fusion technology directions. Our results indicate that for the same plasma physics (*e.g.*, first-stability) and technology extrapolation, steady state operation is more attractive than pulsed-plasma operation. Dramatic improvement over first-stability operation can be obtained through either utilization of high-field magnets (*e.g.*, high-temperature superconductors) or operation in advanced-tokamak modes (*e.g.*, reversed-shear). In particular, if full benefits of reversed-shear operation are realized, as is assumed in ARIES-AT, tokamak power plants will have a cost of electricity competitive with other sources of electricity. In technology area, emerging technologies such as advanced Baryon cycle, high-temperature superconductor, and advanced manufacturing techniques can improve the cost and attractiveness of fusion plants. For blankets, liquid breeder/coolants are the most attractive because most of neutron power is directly deposited in the coolant. This property can be exploited to arrive at a blanket design with a coolant outlet temperature higher than the structure temperature in the radiation zone. The high coolant temperature leads to a high thermal conversion efficiency (as in ARIES-ST and ARIES-AT blankets). The dual-cooled (He and LiPb) ARIES-ST blanket using ferritic steel structural material represents a near-term option for fusion systems and achieves a thermal efficiency of 45%. Development of high-performance SiC composites leads to the high-performance ARIES-AT blanket (SiC composite/LiPb coolant) that achieves 59% thermal conversion efficiency as well as the full potential safety and environmental features of fusion power.

I. INTRODUCTION

Progress in tokamak physics during the past decade has been remarkable. Our vision of tokamak power plants in 1980s, large devices operating in the pulsed mode, is replaced by high-performance, advanced tokamak modes of operation today. During this period, the ARIES team; a national US effort including scientist from universities, national laboratories, and industry; has studied a variety of tokamak

power plants. The research has been aimed at identifying the trade-offs that lead to the optimal regime of operation for a tokamak power plant as well as the critical plasma physics and technology issues. As ARIES designs represents different extrapolation in physics and technology, comparison of these studies highlights the relative contribution of physics and technology advances to the attractiveness of the tokamak concept. Such information is quite valuable in mapping out fusion development path and next-step major facilities.

Four ARIES designs are considered here: The first two, ARIES-I [1] and Pulsar [2] operate in the first-stability regime. Both plasmas have monotonic q profiles and are stable to external kink modes without any need for conducting wall. ARIES-I operates in steady state while Pulsar has a pulsed plasma. Comparison of these two designs in Section II highlights the differences between pulsed and steady-state operation. The other two ARIES designs, ARIES-RS [3] and ARIES-AT [4], operate in reversed-shear mode. Section III presents contributions of advanced tokamak mode of operation to tokamak power plant attractiveness by comparing ARIES-I, ARIES-RS, and ARIES-AT designs.

Continuation of ARIES research has allowed us to apply lessons learned from each ARIES design next. This is especially true in technology areas. In Section IV, we consider fusion power technologies by reviewing He-cooled SiC composite blankets (ARIES-I and Pulsar) and Li-cooled vanadium blankets (ARIES-RS). More recent ARIES work has focused on innovative blanket designs that allow coolant temperature to be higher than structure, resulting to a high coolant outlet temperature and a high thermal conversion efficiency. Examples include dual-cooled ferritic steel design (ARIES-ST [5]) and Li-Pb cooled, SiC composite blanket (ARIES-AT).

Section V includes a summary and implications of this work.

II. STEADY-STATE VS PULSED-PLASMA OPERATION

A. Steady-state first-stability operation

In the late 1980's, operation at high bootstrap current fraction as the approach to steady-state operation was proposed by ARIES-I [1] and SSTR [6] studies simultaneously and independently. In order to reduce the

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current-drive power, the plasma current is reduced while the bootstrap fraction is maximized. In the first-stability regime, this can be accomplished by operating with a moderately high plasma aspect ratio ($A = 1/\epsilon \sim 4.5$) and low plasma current ($I \sim 10$ MA) at a relatively high poloidal beta ($\epsilon\beta_p \sim 0.6$). This mode of operation, however, has to a low value of plasma $\beta \sim 2\%$ because $\epsilon\beta_p$ (which determines the bootstrap fraction) is related to achievable plasma β through

$$\epsilon\beta_p \cdot \beta/\epsilon = (\beta_N/20)^2 S,$$

where $S=(1+\kappa^2)/2$ is the plasma shape factor, κ is the plasma elongation, and β_N is the normalized β . For a conventional first stability configuration (discharges stable to kink modes without a conducting wall) with optimally shaped current and pressure distributions, and with sufficient triangularity in, $\beta_N < 3.5$. Detailed MHD and current drive analysis have showed that a bootstrap fraction of $\sim 60\%$ can be achieved but with a slightly lower $\beta_N \sim 3$. (and a low plasma $\beta \sim 2\%$.) Most of the driven current located near the magnetic axis, requiring a current-drive power of about ~ 100 MW delivered to the plasma. There is ample experimental database for this regime, however, operation in discharges with durations longer than the current diffusion time as well demonstration in a burning plasma are needed.

B. Pulsed-plasma Operation

During 1992-1993, pulsed-plasma operation was considered in the context of Pulsar study. Because the “balance-of-the-plant” can handle only a very small temperature variation in the main coolant (typically $1^\circ\text{C}/\text{min}$), thermal energy storage is necessary – the thermal storage is charged during plasma burn time and is discharged during plasma dwell time. It was argued at the time that as conventional thermal storage systems outside the fusion island tend to be very large and costly, pulsed power plants would be large and expensive and, therefore, economically unacceptable. Pulsar design featured an innovative thermal storage system. We showed that with minimal additional cost, shield could be used as thermal energy storage (for a few 100 seconds) by careful splitting and rerouting of the coolant [7]. Therefore, comparison between pulsed and steady state operation should be made based on other considerations.

In order to have a reasonable power balance, a pulsed tokamak has to operate with a pulse length that is very long compared to dwell time of the discharge (typically several 100s of seconds). Pulsar study showed that optimum pulse length is between 1 to 4 hours; longer pulse lengths are not economical because of additional cost of the OH system. While the OH transformer is quite efficient in driving plasma current, pulsed-plasma operation leads to three important constraints. First, a poloidal field system that is capable of

providing sufficient volt-seconds for 1-4 hour pulse lengths is large and expensive. As a results, optimization of power plants points to a plasma regime of operation with high bootstrap fraction, low current, and high aspect ratio, very similar to that of a steady-state device. Second, as the current profile cannot be controlled and optimized, bootstrap current fraction and β_N tend to be lower compared to those of a steady-state device. Third, because of long pulse duration, the magnetic field generated by the PF system is large. This large and varying field affects the toroidal field system. We found that for the same magnet technology (same superconductor, same structural material), the peak field on the TF system of a pulsed-tokamak device tends to be $\sim 20\%$ lower than the TF system of a comparable steady-state device, leading to a lower power density and a larger tokamak.

A comparison of major parameters of a 1000-MWe steady state and pulsed power plants using *same* physics and technology basis was generated as part of the Starlite study [8] and is shown in Table 1. Our results indicate that both pulsed-plasma and steady-state first stability devices optimize in the same physics regime: low current, high A , and moderate bootstrap current fraction. Because of the long burn time in a pulsed-plasma power plant, plasma is essentially in steady state. As such, physics needs of pulsed-plasma and steady state first-stability devices are identical (the only difference, physics of non-inductive current drive, is well established). As the low recirculating power fraction of pulsed-plasma operation is more than offset by the lower power density, larger size, and the expensive PF system, pulsed power plants tend to be more expensive than steady-state ones -- .A pulsed-plasma power plant is inferior to a steady-state one based on similar physics and technology extrapolations.

TABLE 1.

Major parameters of 1000-Mwe steady-state and pulsed-plasma 1st stability power plants ($A=4$, $\kappa=1.8$)

	<u>Steady State</u>	<u>Pulsed</u>
Major radius (m)	8	8.7
Plasma current (MA)	12.6	15
Bootstrap current fraction	0.34	0.57
β_N	2.9	2.7
β	2.0	2.5
Peak field on coil (T)	16	13
Field on-axis (T)	9	7.5
Ave. wall load (MW/m^2)	1.5	1.2
Recirculating power fraction	0.29	0.06
COE (c/kWh)	10	13

III. DIRECTIONS FOR IMPROVEMENT

Starting from a steady-state, first-stability device, power plant economics can be improved by increasing fusion power density and decreasing the recirculating power fraction. It should be noted that economics improvement with increasing fusion power density “saturates” after a certain limit. At low power density, any reduction in plasmas size (increase in power density and wall loading) proportionally decreases the volume of fusion core (blanket/shield/coils) that surrounds the plasma (and the system cost). However, when plasma size is comparable and/or smaller than the thickness of blanket and shield, the volume of fusion core (and its cost) does not change appreciably with reduced plasma size (increased power density). For 1000-MWe power plants, economic improvements with increased wall loading saturates at an average neutron wall load of ~ 4 MW/m². As a reference, a first-stability steady-state device with a 16-T magnet technology achieves a neutron wall loading of ~ 1.5 MW/m².

High-field magnets can be used to increase the fusion power density as is shown in Table II. (ARIES-I featured a 19-T cryogenic TF system.) Because fusion power density scales as $\beta^2 B^4$, the impact of increased toroidal field is quite dramatic. The increase in fusion power density leads to a substantially smaller device and a slightly lower current-drive power, both factors combine to help improve power plant economics.

Alternatively, one could seek plasma regimes with higher β_N and β that have a large bootstrap current fraction. In 1980s, second-stability operation with a high plasma β was

the focus of theoretical research. However, ARIES-II/IV research [9] showed that high- β second-stability operation leads to bootstrap current overdrive and misalignment of bootstrap current profile with that equilibrium current profile. Therefore, second-stability operation results in only marginal improvements in power plant attractiveness.

Reversed-shear [10] plasmas were proposed in mid 1990s. The benefits of this configuration are that it achieves both high β_N and β , it obtains large bootstrap fractions with very good current profile alignment, and features an internal transport barrier necessary to sustain the peaked pressure profiles that is consistent with the high β and high bootstrap current. The negative central magnetic shear is responsible for stability to ballooning modes. A conducting wall, however, is necessary for stabilization of external kink modes – and the resistive-wall modes should be stabilized with plasma rotation and/or feedback coils.

Reversed-shear regime of operation was analyzed in ARIES-RS and ARIES-AT studies. In both studies, a large database of stable MHD equilibria was generated and their non-inductive current drive needs were calculated. This database was then used by the ARIES Systems Code to arrive at the optimum power plant configuration. Analyses showed that to zeroth order, the cost of electricity is insensitive to the plasma aspect ratio in the range of 2.5 to 4 (lower plasma β at the higher A is compensated by higher toroidal-field strength on axis and lower current-drive power). An aspect ratio of 4 was chosen for both ARIES-RS and ARIES-AT based on engineering considerations.

Table II
Major parameters of 1000-MWe advanced tokamak power plants

	First Stability		Reverse-Shear	
	ARIES-I'	High-field: ARIES-I	ARIES-RS	ARIES-AT
Major radius (m)	8.0	6.75	5.5	5.2
Plasma elongation, κ	1.8	1.8	1.9	2.1
β (β_N)	2% (2.9)	2% (3.0)	5% (4.8)	9.2% (5.4)
Peak field at the coil (T)	16	19	16	11.5
On-axis field (T)	9.0	11	8	5.8
Avg. wall load (MW/m ²)	1.5	2.5	4	3.3
ITER89-P multiplier	1.7	1.9	2.3	2.0
Plasma current (MA)	12.6	10	11.3	13
Bootstrap current fraction	0.57	0.57	0.88	0.91
Current-driver power (MW)	237	202	80	35
Recirculating power fraction	0.29	0.28	0.17	0.14
Thermal efficiency	0.46	0.49	0.46	0.59
Cost of Electricity (c/kWh)	10	8.2	7.5	5

ARIES-RS design achieved a plasma $\beta = 5\%$ ($\beta_N = 4.8$) and a bootstrap current fraction of $\sim 88\%$. Unfortunately, a large current drive power was necessary to drive a relatively “small” plasma current mid plasma and near the plasma edge. Lessons learned from ARIES-RS plasma optimization was applied to ARIES-AT research. Effort was made to eliminate the need for non-inductive current drive in mid-plasma. As a result, while the bootstrap fraction was only increased slightly in ARIES-AT to 0.91, the current-drive power was reduced by a factor of two.

The major difference between ARIES-RS and ARIES-AT is the higher plasma elongation of ARIES-AT ($\kappa=2.1$) that is the result of the ARIES-AT “thinner” blanket. In ARIES design, passive vertical stabilization shells are located behind the blanket. As such, blanket thickness help set the plasma elongation. Higher plasma elongation of ARIES-AT and the corresponding larger plasma triangularity led to a large increase in plasma β to 9.2% with only a slightly higher $\beta_N = 5.4$. ARIES-RS with a $\beta = 5\%$ and a 16-T Nb₃Sn superconductor achieved an average neutron wall loading of 4MW/m². As discussed above, power plant economic performance is insensitive to increased power density above this value. This can be seen in ARIES-AT design point (Table II) where the increased plasma β is used to reduce the toroidal field requirement instead of increasing power density and reducing system size.

As a whole, reverse-shear plasmas achieve the necessary high fusion power density and low recirculating power fraction leading to attractive tokamak power plants with cost of electricity comparable to present sources of energy.

IV. FUSION POWER TECHNOLOGIES

Fusion power technologies (first wall, blanket, shield, and power conversion system) play an important role in the attractiveness of power plant. Not only they must perform the vital function of tritium breeding and power recovery, the safety and environmental characteristics of power plant are mainly determined by the choice of material and the design of these components. In addition, economics of the power plant is directly tied to the performance of fusion power technologies, *i.e.*, thermal conversion efficiency. Three classes of low-activation structural materials are under consideration for fusion applications: ferritic steels, vanadium alloys, and SiC composites. ARIES program have studied blanket designs based on these materials.

Use of SiC composites as advanced structural material for fusion was first proposed in ARIES-I. SiC composites offer a combination of high-performance at high temperature (necessary for high thermal efficiency) as well

as a very low induced activation. Cross section of ARIES-I blanket is shown in Fig. 1. Solid breeder material are located in between SiC composite tube sheets, which are cooled by high-pressure He. ARIES-I design achieved a high coolant outlet temperature of 900°C and excellent safety and environmental characteristics. ARIES-I blanket, however, had two shortcomings. First, the large nuclear heat generation in the solid breeder, especially close to the first wall resulted in small separation between SiC composite tube sheets, making manufacturing of such a blanket difficult. Second, the coolant outlet temperature was too “low” for a reasonable thermal conversion efficiency from Brayton cycles envisioned at the time. As such, a Rankine cycle was used in ARIES-I leading a thermal conversion efficiency of $\sim 46\%$. The performance of ARIES-I blanket was disappointing in this regard as the higher coolant temperature did not lead to a high thermal conversion efficiency.

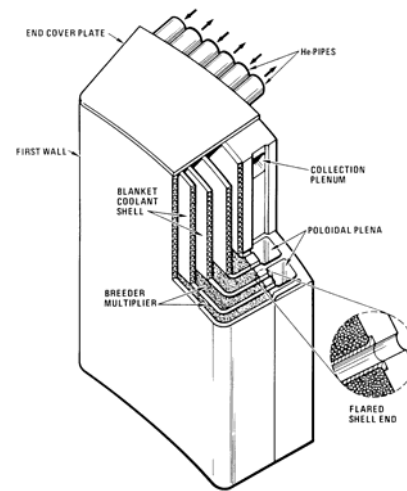


Fig. 1. Cross section of ARIES-I blanket. Solid breeder material are located in between SiC composite tube sheets that are cooled by high-pressure He.

Self-cooled liquid breeder blankets are inherently simpler than blankets with solid breeders as the fusion neutron energy is deposited directly in the coolant. ARIES-RS featured a self-cooled design with liquid lithium as coolant and breeder and vanadium alloy as structural material. High-temperature capability of vanadium alloys allowed a coolant outlet temperature of $\sim 700^\circ\text{C}$ and a thermal conversion of efficiency of 49% (better than ARIES-I due to lower pumping power). Vanadium is a low-activation material and all components of ARIES-RS qualified for shallow land burial under NRC regulations. Lithium/vanadium blankets, however, have two main disadvantageous: 1) Vanadium structure should be coated with an electrical insulator in order to have a reasonable MHD pressure drop and pumping power—such an insulating

V. SUMMARY AND R&D DIRECTIONS

In this paper, we have used the results of ARIES tokamak power plant studies to assess the tradeoffs and relative leverage of advanced plasma physics and fusion technology directions. In physics area, four ARIES designs were considered: The first two, ARIES-I and Pulsar operate in the first-stability regime. Both plasmas have monotonic q profiles and are stable to external kink modes without any need for conducting wall. ARIES-I operates in steady state while pulsar has a pulsed plasma. Our results indicate that both pulsed-plasma and steady-state first stability devices optimize in the same physics regime: low current, high A , and moderate bootstrap current fraction. Because of the long burn time in a pulsed-plasma power plant, plasma is essentially in steady state. As such, physics needs of pulsed-plasma and steady state first-stability devices are identical (the only difference, physics of non-inductive current drive, is well established). As the low recirculating power fraction of pulsed-plasma operation is more than offset by the lower power density, larger size, and the expensive PF system, pulsed power plants tend to be more expensive than steady-state ones -- .A pulsed-plasma power plant is inferior to a steady-state one based on similar physics and technology extrapolations.

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coolant outlet temperatures higher than structure temperature in the radiation zone (which leads to a high thermal conversion efficiency as in ARIES-ST and ARIES-AT blankets). The dual-cooled (He and LiPb) ARIES-ST blanket using ferritic steel structural material represents a near-term option for fusion systems and achieves a thermal efficiency of 45%. Development of high-performance SiC composites leads to the attractive ARIES-AT blanket (SiC composite/LiPb coolant) that achieves 59% thermal conversion efficiency and may achieve the full potential safety and environmental features of fusion power. Such a high performance blanket contributes significantly to the attractiveness of tokamak power plants.

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