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Overview of ARIES-RS tokamak fusion power plant[1]

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Abstract

In order for fusion power to be widely accepted in the next century, it should offer advantages compared to available sources of energy. The Starlite study has examined the ability of tokamak-based power plants to compete with other energy sources. A set of top-level system requirements and goals for system economics, safety and waste disposal, and reliability and availability were established during extensive consultations with US electric utilities and industry representatives. Five different tokamak plasma operation modes were considered and different technology options (e.g. choice of structural material, coolant, breeder) were developed and assessed. Based on this assessment, the ARIES-RS design study was initiated to examine a power plant based on the reversed-shear mode of plasma operation, coupled to a fusion power core which uses high-performance lithium-cooled vanadium components. An overview of the ARIES-RS design is presented in this paper.

1. Introduction

The ARIES-RS tokamak power plant study continues in the tradition of the ARIES Program to establish the economic, safety and environmental potential of magnetic fusion power plants, and to identify physics and technology areas with the highest leverage for achieving attractive and competitive fusion power. The ARIES Team is a national effort with participation from national laboratories, universities and industry, and with strong international collaborations. The Team performs detailed physics and engineering analyses using the most current and detailed models available, and then uses the results to perform optimization and trade studies via a cost-based systems code.

Prior to initiating the design study, a set of top-level system requirements and goals for system economics, safety and waste disposal, and reliability and availability were established through extensive consultations with US electric utilities and industry representatives [1–4]. These requirements were framed in a quantitative way to help establish the minimum necessary features of a fusion power plant that would lead to its likely introduction into the US electric energy supply. The requirements constitute a common basis for quantitative evaluations of any candidate fusion concept.

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Five different regimes of operation were considered: (1) steady-state operation in the first-stability regime, e.g. ARIES-I [5], SSTR [6]; (2) pulsed-plasma tokamak operation, e.g. Pulsar [7]; (3) steady-state operation in the second-stability regime, e.g. ARIES-II and ARIES-IV [8]; (4) steady-state operation with reversed-shear profile; and (5) low-aspect ratio tokamaks (spherical tokamaks). The extent of the plasma physics data base as well as performance as a power plant were considered. In parallel, several options for engineering design were developed and assessed. These options included material choices for the structure, breeder and coolant. The design space for an attractive tokamak fusion power core is not unlimited; previous studies have shown that advanced low-activation ferritic steel, vanadium alloy, or SiC/SiC composites are the only known viable candidates for the primary in-vessel structural material. In order to provide a framework for this assessment, these three material classes were used to distinguish engineering design choices. In each area, the assessment was aimed at investigating: (1) the potential to satisfy the requirements and goals; and (2) the feasibility (e.g. critical issues) and credibility (e.g. degree extrapolation required from present data base). This assessment is reviewed in Refs. [1,9].

While there is no unique design concept guaranteed to succeed, the ARIES team chose to examine a reversed-shear plasma with plasma-facing components using high-performance vanadium-alloy structures cooled by lithium—the ARIES-RS design. This option results in a high-performance fusion core, a necessary ingredient for economically attractive fusion power plants. This paper provides an overview of the ARIES-RS design. More details can be found in Refs. [10–13] in these proceedings and in the ARIES-RS final report [14].

2. ARIES-RS design point

As with previous design studies, ARIES-RS is a conceptual, DT-burning 1000 MWe power plant. The design employs a moderate aspect ratio ($A = 4.0$), low plasma current ($I_p = 11.32$ MA) and high bootstrap current fraction ($f_{BC} = 0.88$). Consequently, the auxiliary power required for rf current drive is relatively low. At the same time, the average toroidal beta is high ($\beta = 5\%$), providing power densities near practical engineering limits (the peak neutron wall loading is 5.68 MW m^{-2}). The TF coil system is designed with relatively 'conventional' materials (Nb_3Sn and NbTi conductor with 316SS structures), and is operated at a design limit of ~ 16 T at the coil in order to optimize the design point. The major parameters of the ARIES-RS power plant are summarized in Table 1. Key systems are described below (see also Refs. [10–13]). Figs. 2–4 of Ref. [10] show, respectively, the reference reversed-shear plasma equilibrium, cut-way of the fusion core and vertical cut through a sector of the ARIES-RS design.

The primary characteristics of a reversed-shear plasma are a hollow current–density profile, a non-monotonic safety-factor (q) profile, and relatively peaked pressure profiles. The hollow current–density profile gives rise to a safety-factor profile, which initially decreases from its value at

Table 1
Operating parameters of the ARIES-RS tokamak power plant

Aspect ratio	4.00
Major radius (m)	5.52
Minor plasma radius (m)	1.38
Plasma vertical elongation (95%)	1.70
Plasma current (MA)	11.32
Bootstrap current fraction	0.88
Toroidal field on axis (T)	7.98
Peak field at the TF coils (T)	16
Toroidal β	0.05
Average neutron wall load (MW m^{-2})	3.96
Primary coolant and breeder	Natural lithium
Structural materials	Vanadium and steel
Coolant inlet temperature (°C)	330
Coolant outlet temperature (°C)	610
Fusion power (MW)	2170
Total thermal power (MW)	2620
Net electric power (MW)	1000
Gross thermal conversion efficiency	0.46
Net plant efficiency	0.38
Recirculating power fraction	0.17
Mass power density (kWe ton^{-1})	66.70
Cost of electricity (mill kWh^{-1})	75.79

the plasma center to a minimum value, and then rises to its value at the plasma edge. It appears that in this regime, the plasma transport is suppressed and a more peaked pressure profile that is consistent with the high β and high bootstrap–current fraction can be sustained. There is ample theoretical research on this regime and some experimental data base is available. Recent experiments on TFTR, DIII-D and JT60-U have demonstrated transiently the improved MHD stability and suppression of plasma particle and energy transport. The experiments each observed strong transport suppression of energy and particles in differing degrees. These experiments have determined that the plasma core is in the second stability regime for ballooning modes. In addition, these experiments obtain β limits consistent with ideal MHD stability predictions, and these are expected to be responsible for the discharge terminations. The global energy confinement times obtained in these experiments have H-factors over ITER89-P scaling of 2–3. In addition, bootstrap current fractions between 50 and 75% have been calculated. Complete demonstration of all the favorable properties simultaneously will require steady state conditions, which are not accessible in present experimental devices. An extensive experimental exploration of this regime of operation is currently on-going.

Analyses of reversed-shear for power plants has shown that to zeroth order, the cost of the device is independent of the plasma aspect ratio in the range of $A = 3$–4 (lower plasma β at the higher A is compensated by higher toroidal-field strength on axis and lower current-drive power). In the ARIES-RS study, an aspect ratio of $A = 4$ was chosen because of engineering considerations. At this aspect ratio and with a plasma current of ~ 11 MA, the maximum theoretical plasma β is $\sim 5.5\%$ (ARIES-RS operates at 90% of maximum β). ARIES-RS uses both active and passive stabilization systems for vertical displacement. Radiatively-cooled tungsten shells which are located between the blanket and shield on the inboard and outboard sides provide passive stabilization. Actively-cooled vertical position coils are placed outboard between the low-temperature shield and the vacuum vessel. Like all configurations with β_N values which exceed the first stability regime this plasma requires a conducting wall to stabilize low-n external kink modes. Stabilization against low-n kink modes are provided by a thickened vanadium 'second wall' behind the first wall cooling channel was shown to provide aufficient conductivity to stabilize kink modes.

The bootstrap–current fraction in ARIES-RS is $\sim 90\%$ and non-inductive current drive is required to supplement bootstrap current. Although the bootstrap current is relatively well-aligned with the required equilibrium current, limitations on wave absorption and conversion required the adoption of three separate rf systems: ion cyclotron fast wave on axis, lower hybrid at the plasma edge, and high-frequency fast wave at the plasma edge. While several candidate current-drive option exists for driving the current in mid-plasma (e.g. high-frequency fast wave, mode conversion), the data base for these current-drive schemes is very small. Each system requires a separate launcher design, however design efforts succeeded in combining all of the hardware into a single special-purpose sector occupying only 0.58% total first wall area. The impacts on tritium breeding and shielding are minimal. About 100 MW of current-drive power is necessary for operation at steady state.

It was determined that operation with a radiative mantle would require both the edge density and plasma Z_{eff} to be too high, resulting in large current drive powers. As a result, a radiative divertor has been used in which most of the power is radiated inside the divertor through injection of neon impurities. With this approach, the peak heat flux at the divertor was kept below 6 MW m^{-2}.

The economics of fusion is such that improvements in many areas will be necessary to produce a competitive product, not the least of which are high power density and high thermal conversion efficiency. While competing technologies, such as combined-cycle fossil-fuel plants, push to ever higher efficiency, it appears necessary that fusion development not constrain itself to modest performance by today's standards. Vanadium alloys offer the promise of both high engineering performance, as characterized by high thermal stress factors and high temperature capability, as well as very attractive safety and environmental features. The chemical reactivity of vanadium is a much more serious concern than with steel. While the possibility of using helium coolant exists (the chief concern is attack of the microstructure by impurities in the He), vanadium is uniquely well matched to pure lithium coolant. Lithium has many well-known virtues, and also well-known concerns over its chemical reactivity. Elimination of water in the power core, as well as protective measures to mitigate the consequences of a spill, were considered to be sufficient to allow the use of lithium as the primary coolant.

While vanadium and lithium can substantially improve the performance of the power core, vanadium is far more expensive than steel alloys. Significant cost savings are obtained by using steel in locations where its use does not sacrifice safety or performance, particularly in the shield. In addition, segentation of the shield into high-temperature and low-temperature zones further allows optimization while retaining 99% of the useful heat for power conversion. Radial segmentation of the blanket maximizes component lifetime and minimizes the waste stream by enabling the rear zones to be reused through several maintenance cycles. In addition, the primary coolant is passed first through the first wall (or divertor plates) at lower temperature to widen the design window, followed by 'superheating' in the rear zones to maximize the outlet temperature. Combined with an advanced Rankine cycle (e.g. see Ref. [1]), a thermal conversion efficiency as high as 46% is expected.

As fusion power plants are capital intensive, a high availability is essential for commercial success. The maintenance scheme follows those of ARIES-IV and Pulsar designs and uses radial removal of an entire sector as a unit. Detailed engineering designs of sectors have been performed to show the feasibility of this maintenance concept. In the ARIES-RS design, the fusion core is divided into 16 sectors (corresponding to 16 TF coils). The entire sector is removed, except for the inboard shield, in a single horizontal motion in order to minimize the plant downtime required for scheduled component replacement and unanticipated repairs [13]. Sectors are removed within maintenance flasks in order to minimize contamination of the containment building. Once inside the hot cells, sectors are disassembled and reassembled prior to the next scheduled downtime. One essential feature of this approach is the complete mechanical and thermal-hydraulic integration of a sector. The mechanical strength of the sector is provided by a continuous 'ring' which transmits the gravity loads vertically through the floor of the vacuum vessel. Even the divertors are integrated into the sector, which is possible only if the divertor plate lifetime is as long as the scheduled sector replacement time. All coolant connections are made behind the shield in the vacuum port region, such that cutting and rewelding (or even mechanical joints) are possible.

In order to remove an entire sector, the outboard legs of the TF coils should be extended radially outward. The minimum achievable distance between the coils and the vacuum port then becomes a critical and limiting parameter. In order to keep the size of the TF coils from becoming too large, and consequently creating massive high-field PF coils, the top and bottom of the TF coils were reshaped away from a constant-tension shape. The large ports between coils for full-sector maintenance, together with the TF coil shaping described above, required innovative solutions for the structural design and support geometry for the TF coils. Several design features achieved this: (a) radially-stacked coil plates are welded together to provide stiffness and a large fraction of the required coil support; (b) intercoil structures were moved above the port, into a rigid keyed crown structure; and (c) additional thick straps were added around the coils to provide both in-plane and out-of-plane support. A bucking cylinder is employed rather than wedging the inboard legs of the TF coils. The magnet systems are the single largest contributor to the capital cost of the fusion power core. Therefore cost-reduction strategies are crucial to further reduce the COE of tokamak power plants. Some benefits have been obtained by grading the superconductor and by limiting the use of Nb_3Sn to high-field regions.

3. System performance and R&D needs

Prior to the start of design studies, targets for the life-cycle cost of electricity were determined in consultation with our Utility Advisory Committee: a requirement of 80 mill $(kWeh)^{-1}$ and a goal of 65 mill $(kWeh)^{-1}$ (in constant 1992 dollars). These targets account for alternatives to fusion likely to exist in the future, recognizing that fusion will enter an increasingly competitive marketplace. Using best estimates for all elements of the cost breakdown, it was determined that the ARIES-RS point design can meet the requirement of 80 mill $(kWeh)^{-1}$, but does not attain the goal of 65 mill $(kWeh)^{-1}$, thought to be representative of the future competition. Thus, further improvements and innovation in the ARIES-RS design should continue to be sought.

Safety and licensing remain top priorities for potential operators of fusion power plants. In the pre-design phase of the project, top-level safety and licensing requirements were established for fusion power systems and a strawman pathway was proposed for the development of fusion regulatory policy and requirements. Two of the dominant concerns are avoiding high-level nuclear waste and reducing the on-site hazard potential to the point where a worst-case accident would not require evacuation of off-site personnel. Through analysis of activation products and LOCA accident scenarios, all components of the ARIES-RS design were shown to meet Class C waste disposal guidelines, and the worst-case LOCA radioactivity releases were demonstrated to result in off-site exposures below 1 rem, such that public evacuation should not be necessary.

In the design of ARIES-RS, an attempt was made to avoid physics and technology extrapolations beyond credible limits. For example, design safety factors were imposed on several key parameters such as the plasma beta limit and peak stresses in the structures. At the same time, advanced physics and engineering were assumed in areas of high leverage. In order to assure these levels of performance in ARIES-RS, critical R&D tasks must be implemented in both physics and technology.

In the tokamak physics area, the physics of reversed-shear plasma (both ignited and at steady state) should be understood resulting in the demonstration of a stable and controllable operating point. Divertor operation and edge physics and integration of the divertor constraints on the plasma operation (edge density, Z_{eff}, current drive power, β limit, etc.) require extensive research.

In the technology area, the development and qualification of low-activation materials remains the key issue. In addition to irradiation testing of small samples, this require research on the response of power core components as material systems, manufacturing, reliability, material lifetime, cost, etc. For the ARIES-RS design, the insulating coating is an additional critical item. Since the plant safety and availability are so dependent on component failures, and because the quantity of data required to establish the needed levels of availability is high, it is imperative to begin a program of engineering testing and to capitalize on all planned and existing irradiation facilities. The simultaneous requirements of high performance under extreme heat and particle loads, together with extended lifetime, maintainability, safety, and radioactive waste pose a difficult problem for divertors and high heat flux components. The lack of predictive capabilities for the edge plasma exacerbates the problem. From an engineering point of view, design solutions and R&D programs are difficult to implement when the goals are unknown.

In summary, the ARIES-RS conceptual design has extended the level of design detail in fusion power plant studies, while maintaining overall performance levels which allow for a potentially attractive end-product. The design demonstrates that with an adequate and successful R&D program, all of the utility requirements can be met. Still, even with optimistic assumptions of the outcome, cost competitiveness and reliability of tokamak-based power plants are sources of major concern, and likely will require further innovations.

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