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UCLA Program in Reactor Studies
The ARIES Tokamak Reactor Study

Progress Report for the period Dec. 1, 1990 to Nov. 30, 1991

The ARIES research program is a multi-institutional effort to develop several visions of tokamak reactors with enhanced economic, safety, and environmental features [1]. The aims are to determine the potential economics, safety, and environmental features of a range of possible tokamak reactors, and to identify physics and technology areas with the highest leverage for achieving the best tokamak reactor.

Four ARIES visions are currently planned for the ARIES program. The ARIES-I design is a DT-burning reactor based on "modest" extrapolations from the present tokamak physics database (*e.g.*, 1st stability operation) and relies on either existing technology or technology for which trends are already in place, often in programs outside fusion. ARIES-II and ARIES-IV are DT-burning reactors which will employ potential advances in physics (*e.g.*, 2nd stability operation with ~100% of plasma current driven by the bootstrap effect). The ARIES-II and ARIES-IV designs employ the same plasma core but have two distinct fusion power core designs; ARIES-II utilize the lithium as the coolant and breeder and vanadium alloys as the structural material while ARIES-IV utilizes helium is the coolant, solid tritium breeders, and SiC composite as the structural material. Lastly, the ARIES-III is a conceptual D-^{3}He reactor.

During the period Dec. 1, 1990 to Nov. 31, 1991, most of the ARIES activity has been directed toward completing the technical work for the ARIES-III design and documenting the results and findings. We have also completed the documentation for the ARIES-I design and presented the results in various meetings and conferences. During the last quarter, we have initiated the scoping phase for ARIES-II and ARIES-IV designs.

1. The ARIES-I Research Activity

The first ARIES design to be completed is ARIES-I, a 1000 MWe power reactor. The ARIES-I research activity was completed in 1990. During this period we have finalized the documentation of the ARIES-I research effort and findings [2,3]. The results of ARIES-I research activities were also presented in several workshops and conferences as invited presentations as listed in the attached list of publications and presentations [4–10].

2. The ARIES-III Research Activity

Most of our activity during this period was focused on ARIES-III design. Technical work for ARIES-III is completed and the results were presented at 14th IEEE meeting at San Diego, CA (Oct. 1991) [11-24].

The ARIES-III activity is the first large-scale investigation of the potential of tokamak as an advance-fuel (D-^{3}He) power reactor. Therefore, an extensive scoping study of D-^{3}He tokamak reactors was first performed before the final design directions for the ARIES-III reactor were chosen. We considered diverse areas such as: (1) physics (power balance) requirements for burning D-^{3}He fuel, (2) MHD beta limits in second stability regime, (3) fueling of a D-^{3}He reactor (production and injection of ^{3}He pellets as well as compact tori injection), (4) choices of coolant and structural material for the first wall and shield, and (5) advanced power conversion schemes (including direct conversion techniques).

The fusion reactivity for D-^{3}He fuel is almost 2 orders of magnitude lower than that of DT fuel. Therefore, to achieve an adequate fusion power density, $P_f \propto \beta^2 B^4$, the βB^2 parameter should be ≥ 1000 % T^2, at least 50 times higher than that of a DT reactor. In addition, the burn temperature, T, for D-^{3}He fuel is about 50 keV, higher than that of a DT reactor. Therefore, a D-^{3}He reactor requires high plasma β, high magnetic field, and high plasma temperature. Since high B and high T result in a highly radiative plasma (both synchrotron and bremsstrahlung radiations) the power balance window for a D-^{3}He tokamak reactor is small.

The synchrotron radiation losses from the plasma depend on the first wall conductivity and "hole" fraction. As a result, a D-^{3}He reactor requires a highly conductive first wall material (or coating) in order to reduce the synchrotron radiation to an acceptable value; material choices are severely limited (W and Be for high temperature operation, and Cu for low-temperature application).

The fusion ash accumulated in the plasma also plays a central role in a D-^{3}He reactor. The fraction of fusion ash in the plasma depends on the parameter τ_{ash}/τ_E, the ratio of ash-particle confinement time to the energy confinement time in the core plasma. As the τ_{ash}/τ_E parameter increases (the fraction of fusion ash increases), the plasma radiation increase. At the same time, for a fixed total plasma β, the fuel ion β is reduced, decreasing the fusion power density. As a result, an increase in the τ_{ash}/τ_E parameter will result in the power balance window to shrink and finally disappear.

Our analyses of a first-stability D-^{3}He reactor showed that power balance can be achieved only for $\tau_{ash}/\tau_E \simeq 1$ (optimistic value of τ_{ash}/τ_E in present experiments is about 4). Furthermore, because the synchrotron radiation scales as $B^{5/2}$, the attractive ARIES-I regime operation for first-stability DT reactors (high aspect ratio, low current, high bootstrap-current fraction, and high field) is inaccessible (*i.e.,* there is an optimum in B regardless of the cost of magnets). Because the fusion power density is low, the plasma β has to be high resulting in a plasma operating with an aspect ratio of ~3 and a high current of ~60 MA. Our analyses showed that even assuming advanced synchrotron current drive to supplement the bootstrap current and assuming the direct conversion of synchrotron radiation by solid state rectennas (at efficiency of 80%) still results in a reactor which is about 50% more expensive than a second-stability version. Therefore, the second stability regime of operation was chosen for the ARIES-III design.

In order to allow for longer a ash particle confinement time $\tau_{ash}/\tau_E \simeq 2$, the ARIES-III should operate in second stability regime with a high plasma $\beta \sim 20\%$. Present theoretical analyses indicate that these high values of β can be achieved only if kink stability requirements are relaxed. Furthermore, this regime of operation leads to a large bootstrap-current overdrive and requires driving plasma current in both direction by the current-drive system. Feedback stabilization of kink modes as well as precise profile control to ensure ballooning stability are also required. The current drive system is based on high-energy (3 to 6 MeV), negative-ion neutral beam injectors because of the need for precise control of the current density profile and predicted relative high current-drive efficiency. Most of the fusion power is radiated in the form of bremsstrahlung and, therefore, almost all of the reactor thermal power is deposited on the first wall and removed by the first-wall coolant circuit.

Because of the high heat flux on the first wall, the choice of coolant is somewhat limited. Helium suffers from poor heat transfer capability. Water-cooled systems lead to inefficient power cycles and result in an expensive reactor. The draw-back for the liquid-metal coolants are activation and MHD effects. Organic coolant appears to be a good choice for the D-^{3}He systems because of high thermal efficiency and good heat transfer capabilities resulting in relatively low-pressure coolant circuit. Organic coolants can be used in a D-^{3}He system (as opposed to a DT reactor) because the reduced neutron yield of D-^{3}He cycle reduces the radiolytic decomposition rate of organic coolant to an acceptable level.

The first wall material and the shield is made of low-activation ferritic steel (HT-9) because it produces the thinnest shield and qualifies as shallow-land burial waste. First wall is coated with 1.45 mm of Be with a thin (0.1 mm) tungsten interface between Be and HT-9. An steam cycle with a thermal conversion efficiency of $\sim$44% is utilized. As a whole, the ARIES-III research indicate that the physics of D-^{3}He tokamak reactors are very demanding. But, if physics parameters can be achieved, the engineering features are attractive (with the exception of the in-vessel components which are subjected to high particle and heat fluxes).

The safety and environmental features of the ARIES-III designs are attractive. the first wall and shield can operate for the life of the plant. After 30 full power years of operation, the shield qualifies as Class-A waste after a cool down period. Activation of the coolant is negligible but disposal of the decomposed coolant is an issue (burning the decomposed coolant is suggested as the option). The ARIES-III design is at least passively safe and may qualify as inherently safe as defined by ESECOM.

3. The ARIES-II and ARIES-IV Research Activity

During the last three months of this period, we have initiated the scoping phase of the ARIES-II and ARIES-IV designs. Both designs operate with the same fusion core but utilize two distinct first wall, blanket, and shield combination. The ARIES-II design uses liquid lithium as the coolant and breeder and vanadium alloys as the structural material. The ARIES-IV utilizes helium as the coolant, solid tritium breeders, and SiC composites as the structural material.

The aim of ARIES-II/IV activity is to examine reasonably-consistent advances in physics to improve the economics of the reactor and also to reduce the required extrapolation in technology as compared to the ARIES-I designs. The major component costs of the ARIES-I fusion power core are the current-drive system (cost and recirculating power) and the magnet system. The ARIES-II/IV designs operate in the second-stability regime but aim at plasma operation such that almost all of the plasma current is provided by the bootstrap effect. This regime of operation leads to plasmas with moderate β (but higher than that of ARIES-I). As a result, substantial savings both in current drive and magnet costs can be made.

The ARIES-II/IV activity is planned to be completed by late spring 1992.

ARIES Project Publications and Invited Presentations
for the period Dec. 1, 1990 to Nov. 30, 1991

[1] R. W. Conn and F. Najmabadi, "Visions of the Future, A Program in Tokamak Reactor Studies," University of California Los Angeles report UCLA-PPG-1201 (Dec. 1987).

[2] F. Najmabadi, R. W. Conn, *et al.* , "The ARIES-I Tokamak Reactor Study, the Collection 14 papers presented at the ANS 9th Topical Meeting," University of California Los Angeles report UCLA-PPG-1339 (Dec. 1990).

[3] F. Najmabadi, R. W. Conn, *et al.* , "The ARIES-I Tokamak Reactor Study—The Final Report," University of California Los Angeles report UCLA-PPG-1323 (1991).

[4] F. Najmabadi, R. W. Conn, *et al.* , "The ARIES-I— Tokamak Reactor Study," *Proc. 16th Symp. Fusion Technol. (SOFT),* London, United Kingdom (Sept. 1990), *Fusion Technology 90*, B. E. Kenn, M. Huguet, and R. Hemsworth, Eds., North-Holland, Amsterdam (1991) p. 253

[5] R. W. Conn, F. Najmabadi, *et al.* , "ARIES-I, A Steady State, First-Stability Tokamak Reactor with Enhanced Safety and Environmental Features," in *Proc. 13th Int. Conf. on Plasma Phys. and Controlled Nucl. Fusion Research,* Washington, D.C. (Oct. 1990), International Atomic Energy Agency, Vienna (1991)

[6] F. Najmabadi, "Steady State Reactors and ARIES Perspective," Presented at Steady-State Tokamak Experiment Workshop, San Diego, CA (Nov. 1990).

[7] M. Kikuchi, R. W.Conn, F. Najmabadi, and Y. Seki, "Recent Directions in Plasma Physics and its impact on Tokamak Magnetic Fusion Design," *Proc. of 2nd Int. Symp. on Fusion Nucl. Technol.*, Karlsruhe, Germany (June 1991), to be published in Fusion Eng. Des. (1992).

[8] S. Sharafat, F. Najmabadi, and C. P. C. Wong, "The ARIES-I fusion power core," in *Proc. of 2nd Int. Symp. on Fusion Nucl. Technol.*, Karlsruhe, Germany (June 1991), to be published in Fusion Eng. Des. (1992).

[9] R. W. Conn and F. Najmabadi, "Overview of the ARIES Tokamak Reactor Study," Presented at DOE Headquarters, Germantown (Sept. 1991). .

[10] F. Najmabadi, "Environmental and Safety Aspects of Fusion Power," Special Evening Invited Program, Annual American Physical Society, Division of Plasma Physics Meeting, Tampa, Florida (Nov. 1991).

[11] F. Najmabadi, R. W. Conn, *et al.* , "The ARIES-III D-^{3}He Tokamak Reactor," in *Proc. IEEE 14th Symp. on Fusion Eng.,* San Diego, CA (Oct. 1991), IEEE, Piscataway, NJ (1992).

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[13] T. K. Mau, J. Manderakas, D. Ehst, J. H. Whealton, and the ARIES Team, "Current Drive and Profile Control for the ARIES-III Second-Stability Advanced-Fuel Tokamak Reactor," in *Proc. IEEE 14th Symp. on Fusion Eng.,* San Diego, CA (Oct. 1991), IEEE, Piscataway, NJ (1992).

[14] G. A. Emmert, E. A. Mogahed, C. Kessel, J. Mandrekas, T-K. Mau, and the ARIES Team, "Plasma Startup of the ARIES-III Second-Stability Advanced Fuel Tokamak," in *Proc. IEEE 14th Symp. on Fusion Eng.,* San Diego, CA (Oct. 1991), IEEE, Piscataway, NJ (1992).

[15] C. Bathke, S. Jardin, and C. Kessel, "An Algorithm for Determining EF Coils from Fixed-Boundary Equilibria Applied to ARIES-III," in *Proc. IEEE 14th Symp. on Fusion Eng.,* San Diego, CA (Oct. 1991), IEEE, Piscataway, NJ (1992).

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[20] C. P. C. Wong, K. R. Schultz, E. T. Cheng, S. Grotz, M. Hasan, F. Najmabadi, S. Sharafat, J. Brooks, D. Ehst, D-K. Sze, S. Herring, C. Walters, J. Bartlit, M. Valenti, D. Steiner, and the ARIES Team, "ARIES-III Divertor Engineering Design," in *Proc. IEEE 14th Symp. on Fusion Eng.*, San Diego, CA (Oct. 1991), IEEE, Piscataway, NJ (1992).

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[23] S. K. Ho and the ARIES Team, "Controlled Central Fueling for ARIES-III by Compact-Toroid Injection," in *Proc. IEEE 14th Symp. on Fusion Eng.*, San Diego, CA (Oct. 1991), IEEE, Piscataway, NJ (1992).

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