The ARIES–III D-^{3}He Tokamak Reactor Study

J.F. Santarius and the ARIES Team

January 1992

UWFDM-874

Presented at the US-USSR Workshop on D-3He Reactor Studies, 25 September – 2 October 1991, Moscow.

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

The ARIES–III D-^{3}He Tokamak Reactor Study

J.F. Santarius and the ARIES Team

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

January 1992

UWFDM-874

Presented at the US-USSR Workshop on D-3He Reactor Studies, 25 September – 2 October 1991, Moscow.

The ARIES–III D-^{3}He Tokamak Reactor Study

John F. Santarius
University of Wisconsin, Madison, WI 53706

and the ARIES Team

Abstract

This paper briefly summarizes the key features of and issues for a preliminary version of the ARIES-III commercial tokamak reactor conceptual design. The ARIES project is a national study by the U.S. fusion community of various visions of a commercial tokamak reactor. ARIES-III has been designed to produce 1000 MWe from a tokamak utilizing the D-^{3}He fuel cycle and operating in the second-stability MHD regime. Features of the device include the use of an organic coolant in the thermal power conversion cycle, a low releasable radioactive inventory during credible accidents, a first wall and shield that could survive a loss-of-coolant accident without structural damage, and a 'conventional,' high-recycle divertor. The final report [1] for the ARIES-III study is in progress, so the present information should be regarded as subject to change. The ARIES-III final report should be consulted for official reference parameters and detailed design descriptions.

1. Overview

The ARIES, *Advanced Reactor Innovation and Evaluation Study*, project is designing several variants of commercial tokamak fusion reactors, with broad participation, primarily by the U.S. fusion community [1, 2]. The principal groups participating in the ARIES project are shown in Fig. 1.

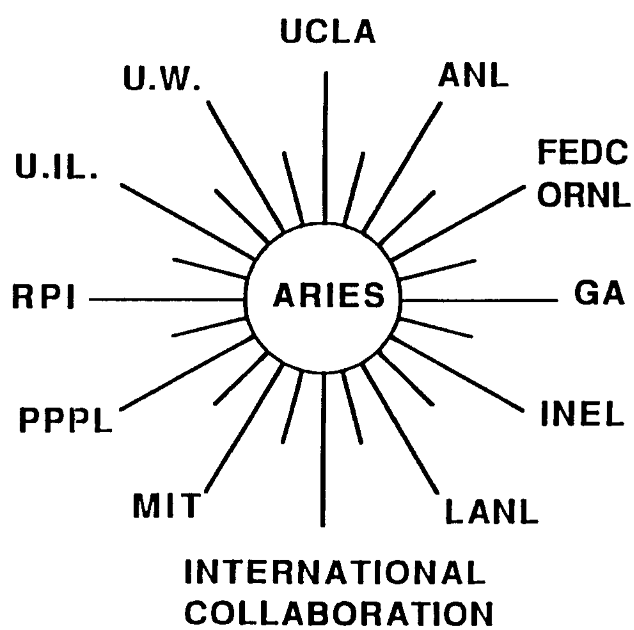

Figure 1. *Principal ARIES project participants.*

ARIES-III is one of three tokamak reactor *visions* being designed in detail within the ARIES project. The three visions are:

1. ARIES-I: A D-T, first-stability regime tokamak extrapolated from the ITER physics data base;
2. ARIES-II: A D-T, second-stability regime tokamak; and
3. ARIES-III: A D-^{3}He, second-stability regime tokamak.

The ARIES-I final report is in press, the ARIES-III report in in final edit, and the ARIES-II study is scheduled to be completed in March, 1992. Other options considered for ARIES-III were operation in the first-stability regime and utilization of the spherical torus configuration—that is, a very low aspect ratio tokamak.

The primary objectives for the ARIES-III study were to:

- Develop self-consistent design approaches for D-^{3}He tokamak reactors.
- Determine potential economic, safety, and environmental features of this class of tokamak reactors.
- Identify critical physics and technology issues for D-^{3}He tokamak reactors.
- Identify key issues that are specific to D-^{3}He tokamak reactors.
- Identify key areas where use of D-^{3}He fuel has resulted in improvements in reactor performance.

A viable, D-^{3}He tokamak reactor—in comparison to a D-T tokamak reactor—must overcome the relatively low fusion power density in the plasma. Figure 2 shows that, at the ion temperature corresponding to the peak power density for the respective fuel cycle, D-T fuel has about an 80 times higher power density than a 1:1 mixture of ^{3}He and D. For a 1:2 ^{3}He:D mixture, the power density can be increased somewhat, but with an increased neutron production due to D-D reactions. The neutron production from these fuel cycles is shown in Fig. 3. In order to compete in the market-

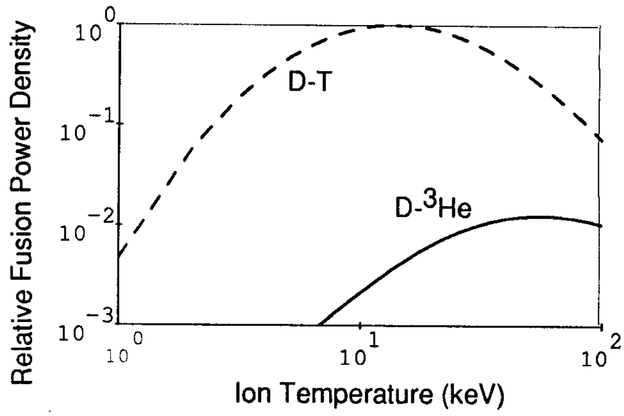

Figure 2. *Local fusion power density in the plasma for D-T and D-^{3}He fusion fuels.*

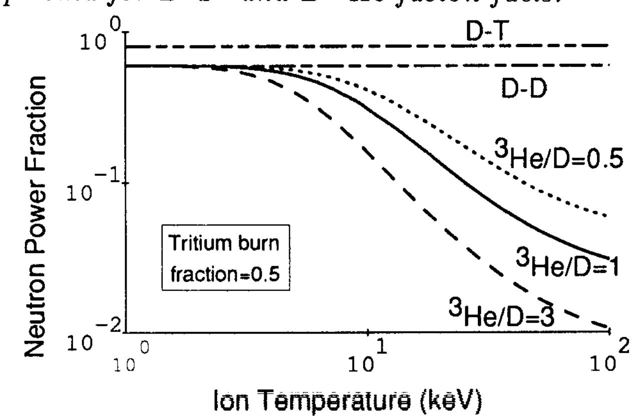

Figure 3. *Ratio of neutron power to fusion power for the D-^{3}He, D-T, and D-D fusion fuel cycles. Several values of the ratio of ^{3}He to D density are given for D-^{3}He.*

place with a D-T reactor, a D-^{3}He reactor must demonstrate that the engineering advantages derived from the reduced neutron flux and increased charged-particle power fraction can compensate for the physics difficulties caused by the reduced plasma power density.

The key parameters of ARIES-III are listed in Table 1.

Table 1. *Key parameters for the ARIES-III D-^{3}He commercial tokamak reactor design (preliminary).*

Plasma major radius	7.5	m
Plasma minor radius	2.5	m
Toroidal B-field on axis	7.6	T
Toroidal beta	24	%
Plasma current	30	MA
Electron temperature	53	keV
Electron density	3.3×10^{20}	m^{-3}
Ion density	2.1×10^{20}	m^{-3}
Z_{eff}	2.0	
Total fusion power	2682	MW
Net electric power	1000	MWe
Recirc. power fraction	24	%
Ave. neutron wall load	0.079	MW/m^2

2. ARIES-III Physics

Because of the relatively low fusion power density for a D-^{3}He plasma, the operating-space design window is limited. Coupled with the high plasma temperature and high magnetic field, this leads to the constraint that the first wall must be highly reflective to synchrotron radiation, so that most of the synchrotron radiation produced is reabsorbed in the plasma. This limits the choice of coating materials for the first wall to copper, beryllium, or tungsten; for ARIES-III, beryllium has been chosen. The required energy confinement time is ~7 times the ITER-89P multiplier, or about twice that of the recently discovered VH-mode [3]. The small design window and the large energy confinement time required also lead to a design point with a fusion-ash particle confinement time to energy confinement time ratio of $\tau_p^{ash}/\tau_E^{bulk} = 2$. The assumption of a smaller $\tau_p^{ash}/\tau_E^{bulk}$ ratio would allow a somewhat lower confinement multiplier. The relation of these values for ARIES-I, ARIES-III, and a D-^{3}He first-stability tokamak to the present data base is shown in Fig. 4.

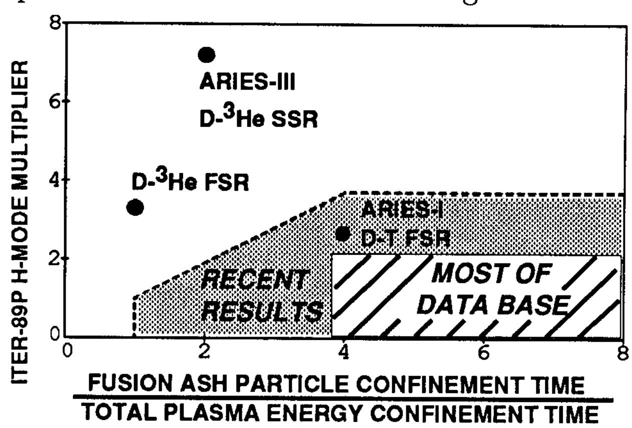

Figure 4. *Comparison of the ARIES first and second stability tokamak reactor cases with regard to energy confinement and to the ratio of fusion-ash to fuel-particle confinement.*

The MHD equilibrium and stability properties of ARIES-III have been investigated in considerable detail—leading to a second-stability design point at $\beta = 24\%$. Precise profile control is necessary to ensure ballooning stability, as is feedback control of kink modes. An unanticipated difficulty of operation in the second-stability regime is that the bootstrap current constitutes a large overdrive beyond the plasma current necessary for equilibrium. This leads to a large external power for current drive. Neutral beams were chosen over fast waves, primarily because neutral beams provide about twice the efficiency in driving the current for ARIES-III parameters.

A D-T startup phase is used in ARIES-III, leading to ~1000 MW of neutron power lasting for ~140 s. The increased neutron heating can be handled by the magnets, but ~100 MW of additional ICRF power beyond that absorbed from the neutral beams is required during startup.

A 'conventional,' high-recycle divertor appears to be viable, assuming L-mode plasma scaling at the edge, but design margins are small. The divertor plates are coated with a 4-mm layer of tungsten to reduce erosion during disruptions. During a disruption, the thermal energy dissipated is about 10 GJ, and the magnetic energy dissipated is about 5 GJ. Assuming a thermal quench time of 0.1–1 ms and a pessimistic vapor shielding factor of two, the resulting vaporization is about 0.2 mm Be for the first wall, and 3.9 mm W for the divertor. Higher vapor-shielding factors will reduce the erosion proportionately, but the plates will require recoating after a few disruptions. Assuming a current quench time of 5–100 ms, initial analyses indicate that the electromagnetic forces give rise to only a few tenths of a MPa of pressure on the steel shield structure, so that the ARIES-III shield should be robust against a current quench.

3. ARIES-III Engineering

The ARIES-III shield will be constructed of a modified HT-9 alloy, with greatly reduced concentrations of niobium, molybdenum, and nickel. This leads to a substantial reduction of the neutron-induced, long-lived radioactivity and to a permanent shield. In contrast, the first wall and blanket of a typical D-T fusion reactor must be replaced five to ten times during the reactor's lifetime. The ARIES-III shield will qualify as Class A, low-level waste.

A key element of the ARIES-III design is that the afterheat is so low that a loss-of-coolant accident (LOCA) will neither melt the structure nor degrade the properties of the materials—so that protection of the economic investment is assured. The releasable radioactive inventory during credible accidents is also calculated to be low.

The outboard shield module is shown in Fig. 5. The 0.6 mm steel first wall is coated with a 1.5 mm thick layer of beryllium to efficiently reflect the synchrotron radiation produced by the plasma and to protect the steel first wall against disruptions. A 100 μm layer of tungsten is located between the beryllium and the steel structure to prevent their interaction. The tritium production rate in the Be layer, the first wall, and the shield is <90 Ci/d, and the induced radioactivity in the coolant is very low.

The reduced neutron flux of the D-^{3}He fuel cycle allows the use of an organic coolant for the thermal power conversion cycle, because there is much less radiolytic decomposition than there would be in a D-T fusion reactor. Organic coolants operate at low pressure, allow high temperature, possess

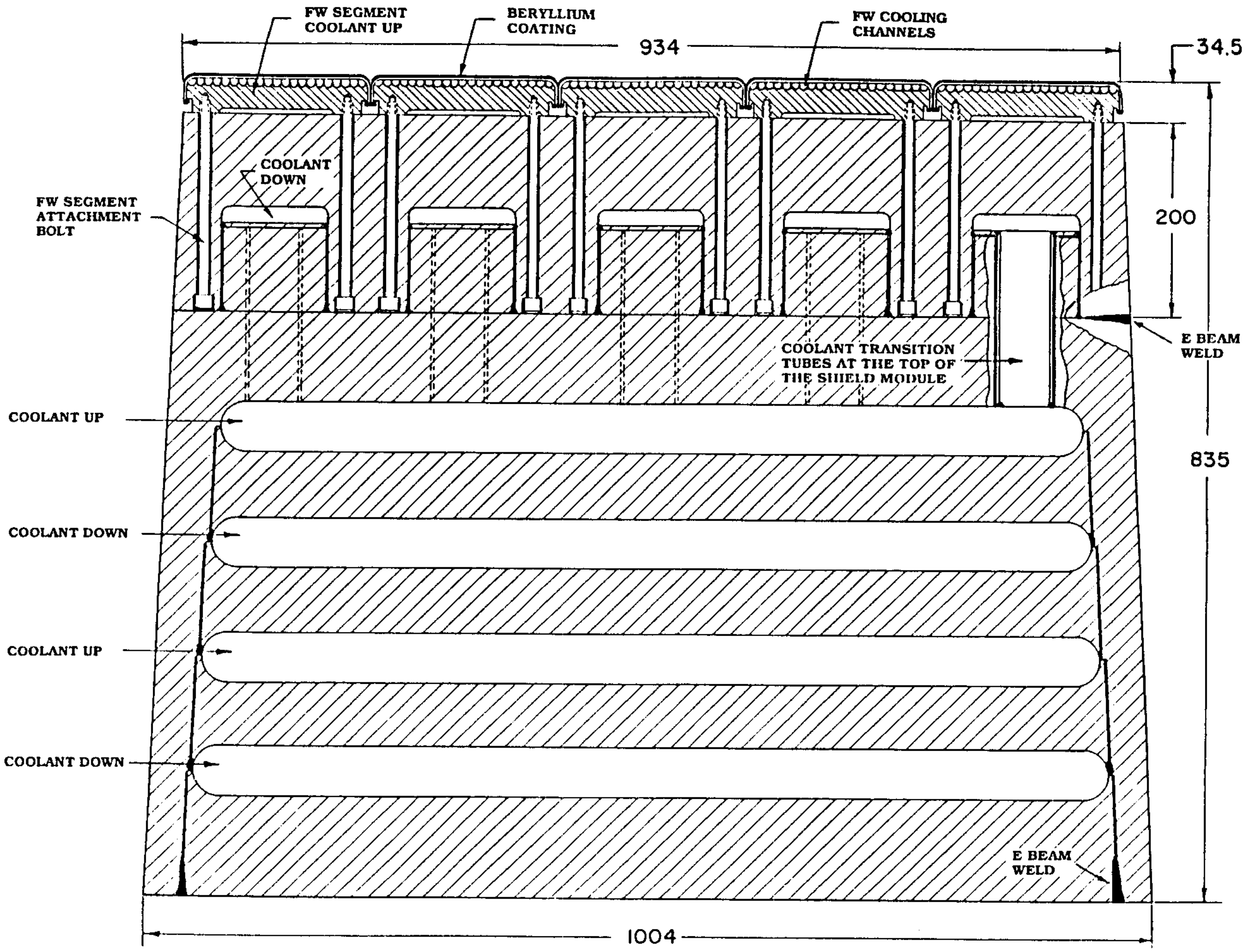

Figure 5. *Schematic view of the ARIES-III outboard shield module in mid-plane cross section.*

good heat-transfer characteristics, and generate very little corrosion. They do, however, decompose by both radiolysis and pyrolysis, thus requiring some coolant replacement, fast flow to avoid choking, and chemical waste disposal. The organic coolant HB-40 has been chosen for the reference case, and the power cycle efficiency is 44%.

4. Comparison of Key Issues for First and Second Stability Regime Operation

In the process of selecting the second-stability regime for the reference ARIES-III design, the ARIES team also examined the first-stability regime. A comparison of the key issues for these regimes is given in Table 2.

Table 2. *Key issues for first and second stability, D-^{3}He, tokamak reactors.*

First Stability Regime	Second Stability Regime
$\tau_p^{ash} \leq 1.5\tau_E^{bulk}$	$\tau_p^{ash} \leq 3\tau_E^{bulk}$
H-mode confinement factor ~3.5	H-mode confinement factor ~7
Plasma current >50 MA	Plasma current >30 MA
Bootstrap current fraction ~40%	Bootstrap current overdrive
Synchrotron current drive	Careful tailoring of plasma profiles
Rectenna synchrotron radiation conversion	Second stability regime experimental verification

Although the first-stability case is closer to the present energy-confinement data base, the particle-confinement limit for the fusion ash is more stringent than that of the second-stability case—possibly necessitating active pumping of the fusion ash. There is substantial overdrive of the plasma current in the second-stability case, but the bootstrap current in the first-stability case is only ~40% of the plasma current, so that the use of synchrotron radiation current drive to limit the total external current-drive power is required. The predicted cost of electricity in the second-stability case is somewhat lower than that of the first-stability case, which invoked high-efficiency rectenna conversion of synchrotron radiation—an interesting technology that requires some extrapolation from the present data base.

There were various viewpoints within the ARIES team regarding the technical feasibility and attractiveness of these options, and the majority of the ARIES team favored the second-stability regime for the reference ARIES-III design.

5. Conclusions

A detailed, integrated design of a second-stability, D-^{3}He, commercial tokamak reactor, ARIES-III, has been performed. Several physics requirements are a significant extrapolation beyond the present data base and require verification. These include: second-stability regime operation, a high energy confinement factor, a relatively small design window, strict profile control, and an active kink stability control system. A D-T startup phase appears necessary, requiring ~100 MW of additional ICRF power.

The engineering requirements are modest for the shield, and are generally not more difficult than those of a D-T reactor, except for the first-wall design, where a beryllium coating is necessary to reflect synchrotron radiation efficiently. Advantages include: elimination of a tritium breeding blanket, use of organic coolant in a 44% efficient power cycle, a first wall and shield design that can survive a loss-of-coolant accident without structural damage or significant radiation release, and a low releasable radioactive inventory during credible accidents. The cost of electricity is comparable to that of the first-stability, D-T reactor, ARIES-I.

Acknowledgement

This research was funded by the U.S. Department of Energy.

References

[1] F. Najmabadi, R.W. Conn, et al., "The ARIES-III Tokamak Reactor Study—Final Report," UCLA Report UCLA-PPG-1384 (1992).

[2] F. Najmabadi, R.W. Conn, et al., "The ARIES-III D-^{3}He Tokamak-Reactor Study," *Proc. 14th IEEE Symposium on Fusion Engineering* (IEEE, NY, 1992).

[3] T.C. Simonen, "Recent Results from DIII-D," *Proc. 14th IEEE Symposium on Fusion Engineering* (IEEE, NY, 1992).