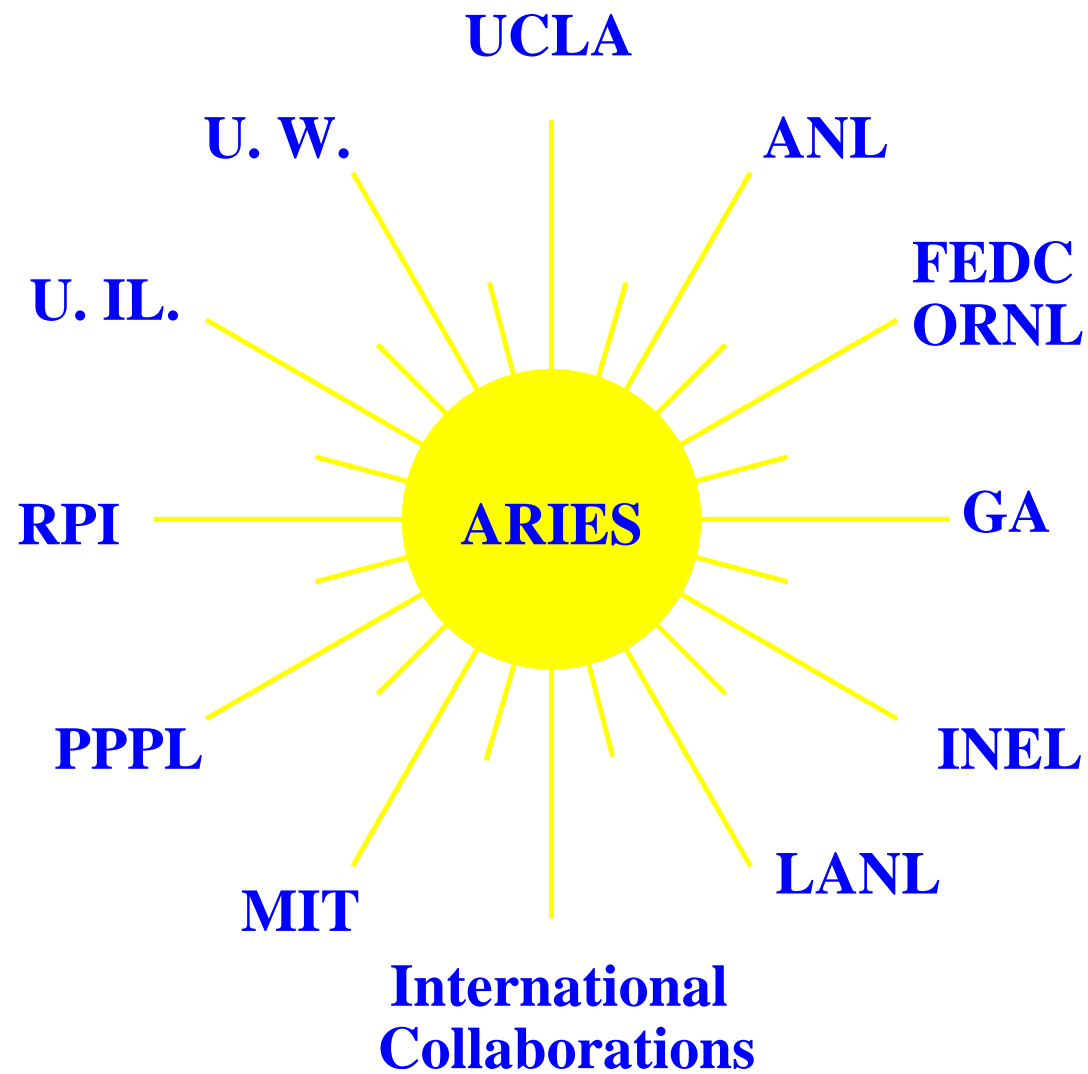


THE ARIES-III
D-³He TOKAMAK REACTOR STUDY

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for The ARIES Team

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ARIES Is a Community-Wide Study



Primary Objectives

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

Physics Requirements

- $P_f \propto \frac{\langle \sigma v \rangle}{T^2} \beta^2 B^4$

Comparing D-³He to DT:

$$\frac{\langle \sigma v \rangle}{T^2} \downarrow \sim 100 \implies \beta B^2 \uparrow \sim 5 - 10$$

	<u>DT</u>	<u>D-³He</u>
Temperature (keV)	10–20	50
βB^2 (% T ²)	≥ 200	≥ 1000

- Requires high β , high B , and high T .

Physics Requirements

- High T and high B result in a highly radiative plasma:*

$$P_{brem} \propto Z_{eff} n_e^2 T_e^{1/2}$$

$$P_{syn} \propto n_e^{1/2} T_e^{5/2} B^{5/2} \sqrt{1 - R_{syn}}$$

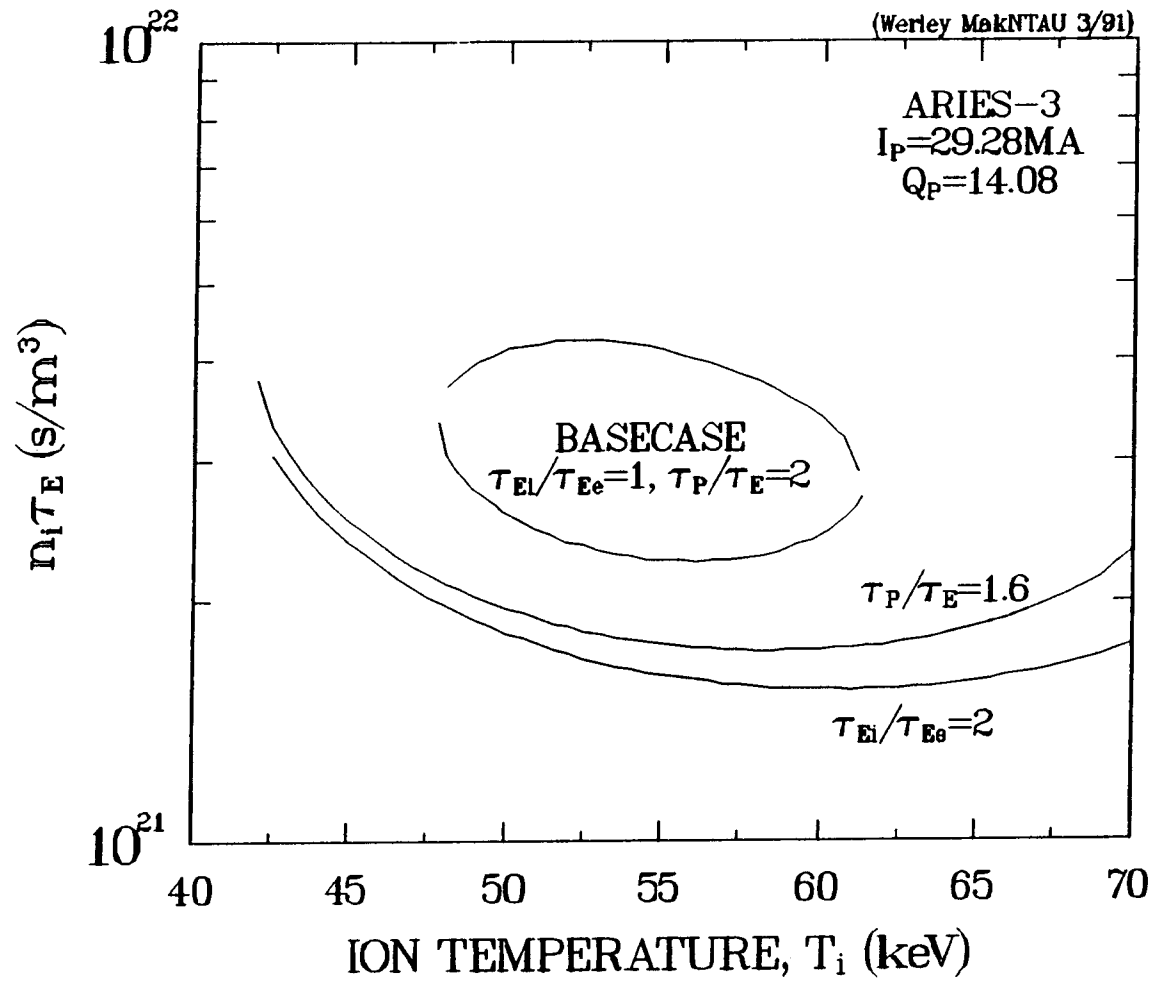
$$R_{syn} = (1 - f_h) (1 - \sqrt{2\epsilon_0 Z^* \omega_c \rho})$$

$f_h \equiv$ first-wall “hole” fraction.

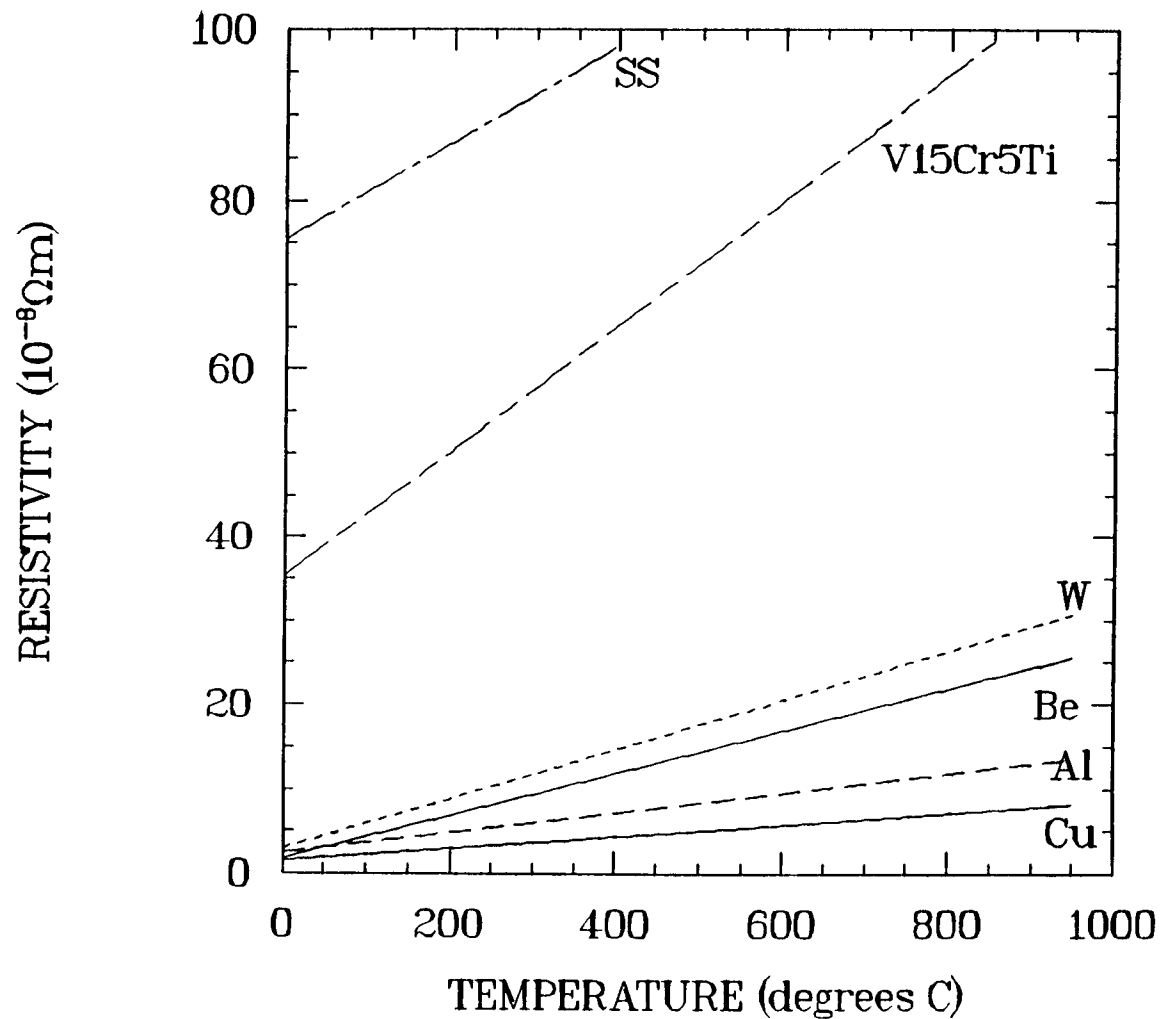
$\rho \equiv$ first-wall electrical conductivity.

- ★ Fully relativistic formulas are used in actual calculations.

Physics Requirements



Electrical Resistivity of Some Material



Physics Requirements

- Power balance requirements result in a small design window:

- ★ Highly reflective first wall and small hole fraction.

First wall should be coated with Cu, Be, or W.

- ★ Stringent ash exhaust limits:

$$\tau_p^{ash} / \tau_E^{bulk} \leq 1 - 1.5 \text{ for 1st stability regime.}$$

$$\tau_p^{ash} / \tau_E^{bulk} \leq 2 - 3 \text{ for 2nd stability regime.}$$

- Start-up in D-³He requires ≥ 500 MW of auxiliary power. Start-up with a DT phase is needed. The reactor has to be steady state.
- Thermal stored energy in the plasma is ~ 10 times that of a DT reactor. Thermal load during a disruption is a major issue.

1st Stability D-³He Tokamak Reactor

- Since $P_{syn} \propto B^{2.5}$, there is an optimum in the field (~ 20 T).
- Requires $\tau_p^{ash} / \tau_E^{bulk} \leq 1 - 1.5$.
- Requires high β ($\geq 6\%$):
 - ★ Low aspect ratio (~ 3);
 - ★ High Current (≥ 50 MA);
 - ★ Low bootstrap fraction ($\sim 40\%$).
- Requires efficient current drive. (synchrotron CD?)
- Requires direct conversion of synchrotron radiation.

2nd Stability D-³He Tokamak Reactor

- Requires high β and high β_p to reduce B and synchrotron power substantially:
 - ★ Requires $\tau_p^{ash} / \tau_E^{bulk} \leq 2 - 3$.
- Requires high β ($\sim 20\%$):
 - ★ Low aspect ratio (~ 3);
 - ★ High confinement enhancement factor ($H \geq 7$);
 - ★ Careful tailoring of plasma profiles (n , T , and j_ϕ).
- Thermal power conversion.

ARIES-III Reference Design

2nd Stability operation is chosen for the ARIES-III reference design because:

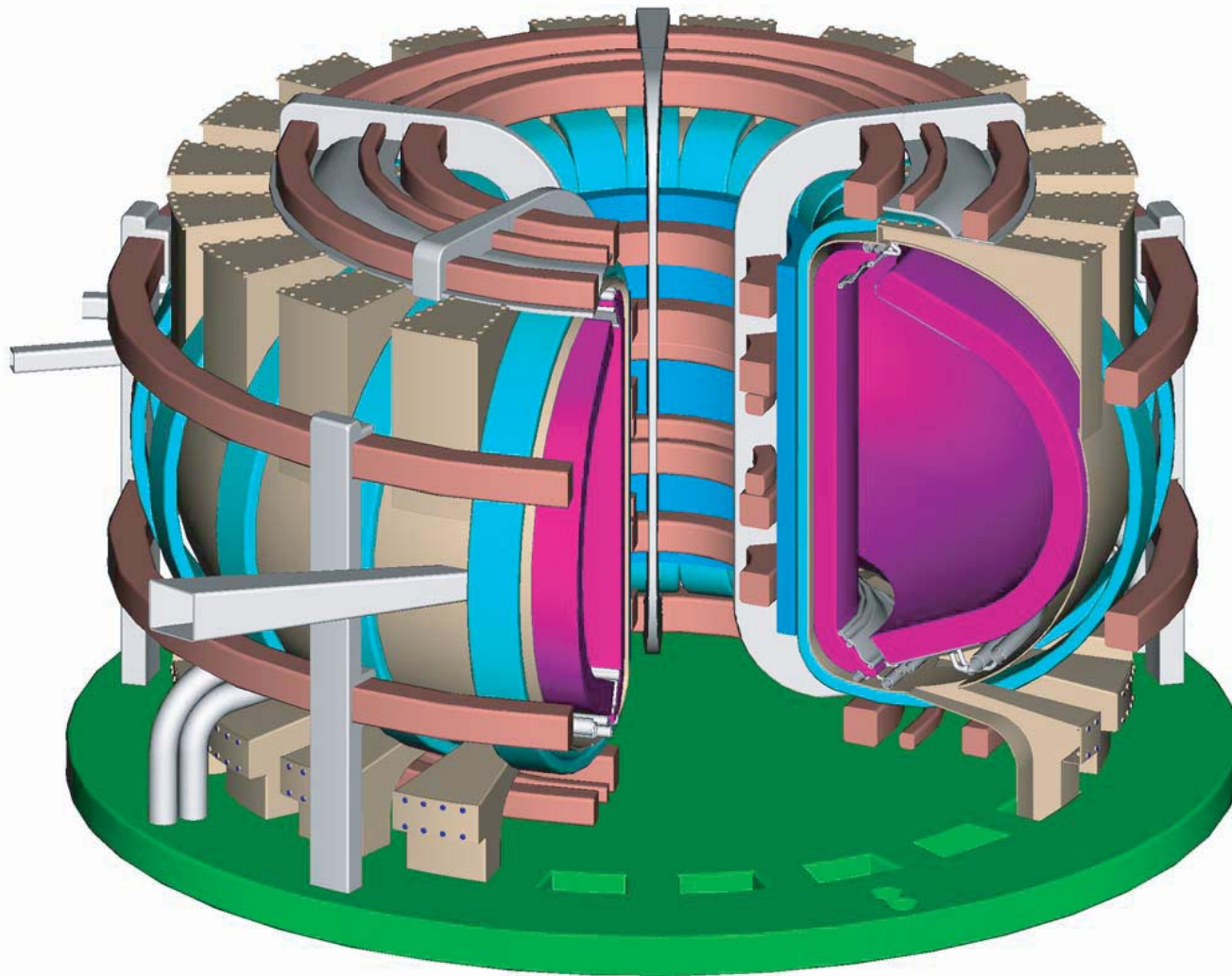
- 1st stability requires $\tau_p^{ash} / \tau_E^{bulk} \sim 1$.
- 1st stability requires efficient current drive (Sunchrotron CD).
- 1st stability requires direct conversion with rectannas.
- For the same $\tau_p^{ash} / \tau_E^{bulk}$, 2nd stability costs less.

ARIES-III Major Parameters

Second Stability Operation

Aspect ratio	3.0
Plasma major radius (m)	7.5
Plasma minor radius (m)	2.5
Toroidal field on axis (T)	7.5
Plasma current (MA)	30
Toroidal beta	24%
Electron density ($\times 10^{20} \text{ m}^{-3}$)	3.6
Ion density ($\times 10^{20} \text{ m}^{-3}$)	2.3
Electron temperature (keV)	48
Z_{eff}	2.0
Neutron wall loading (MW/m ²)	0.1
Net electric power (MWe)	1000
Recirculating power fraction	0.25

The ARIES-III D-³He Tokamak Reactor



Physics Features of ARIES-III

Confinement

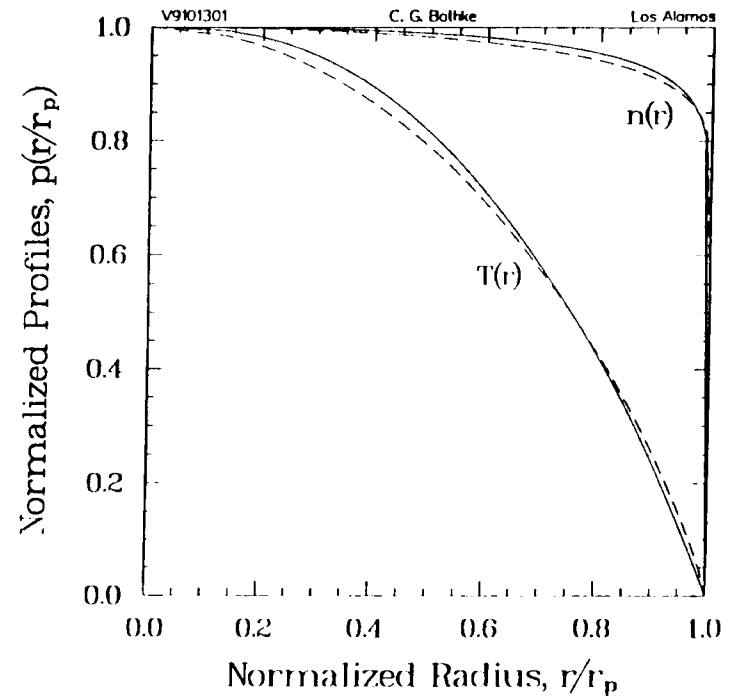
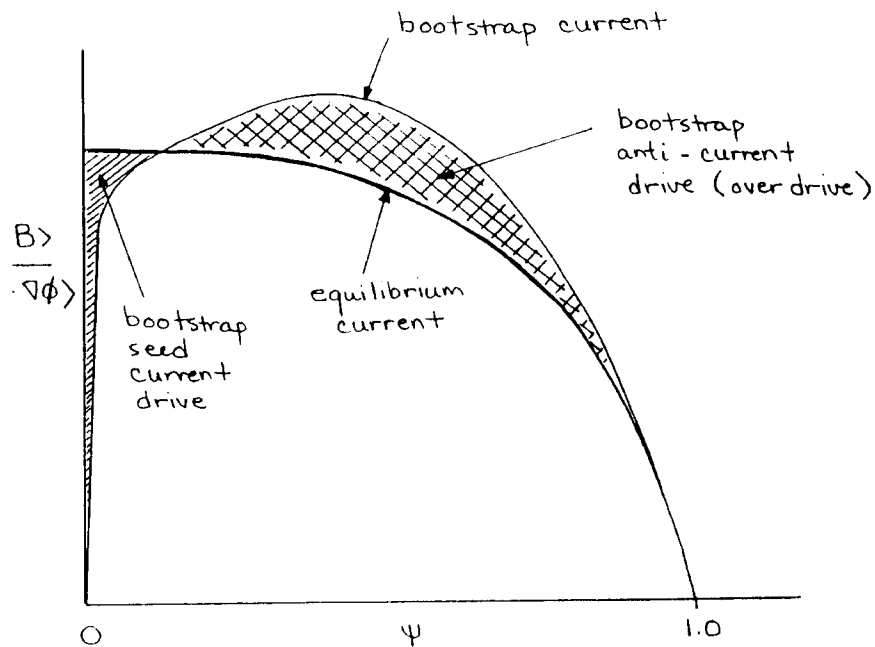
- $\tau_p^{ash} / \tau_E^{bulk} = 2$ ($\tau_E = 13.7$ s).
- Confinement enhancement $H_{ITER-P} \simeq 7.6$

Equilibrium & Stability

- 2nd stability operation at $\beta = 24\%$ ($C_T = 15$).
- Large β at $\epsilon\beta_p \sim 1$ results in $A \simeq 3$.
- Very precise profile control is necessary to ensure ballooning stability.
- Feed-back control of kink modes is required.

Plasma Profiles

- p and j_ϕ profiles are optimized for high β at $\epsilon\beta_p \sim 1$.
- n profile is chosen to minimize bootstrap current.



Physics Features of ARIES-III

Current drive

- Required for control of current profile for MHD stability.
- High efficiency is required.
- 6-MeV NBI for seed current (48 MW).
- 3-MeV NBI for reverse current (146 MW).
- Current drive efficiency: 0.06 A/W.
- NBI based on RFQ with system efficiency of 0.68.
- Beam-plasma reaction produces 21.6 MW of fusion power (^3He beams not feasible because of $^3\text{He}^-$ source problems and low CD efficiency of 0.02 A/W).

Physics Features of ARIES-III

Impurity control

- Because transport power is low, high-recycling divertors appear feasible.
- Peak heat flux is $\sim 5 \text{ MW/m}^2$ and $T_e < 30 \text{ eV}$.
- Target armor is 4 mm of W. Can withstand thermal load of only one disruption.

Fueling

- Both pellet and CT injection are considered. Issues:
 - ★ ^3He pellet production and injection.
 - ★ CT acceleration power.

ARIES-III Magnets

- $B_{\text{coil}} = 14 \text{ T}$.
- Use of a ferritic shield results in ferromagnetic reduction of ripple.
- 20 shell-like coils with large out-of-plane strength.

Support caps to handle fault conditions.

- High-strength structural alloy (700 MPa), high-strength stabilizer, and demountable cryostats.
- Large energy margin in the innermost turns to absorb nuclear heating of the DT start-up.
- PF coils have similar conductor and structure.
- PF coil design is driven by the need to provide and maintain plasma current during the start-up.
- Pulsed losses in the TF and PF system due to helical feed-back control coils need to be determined.

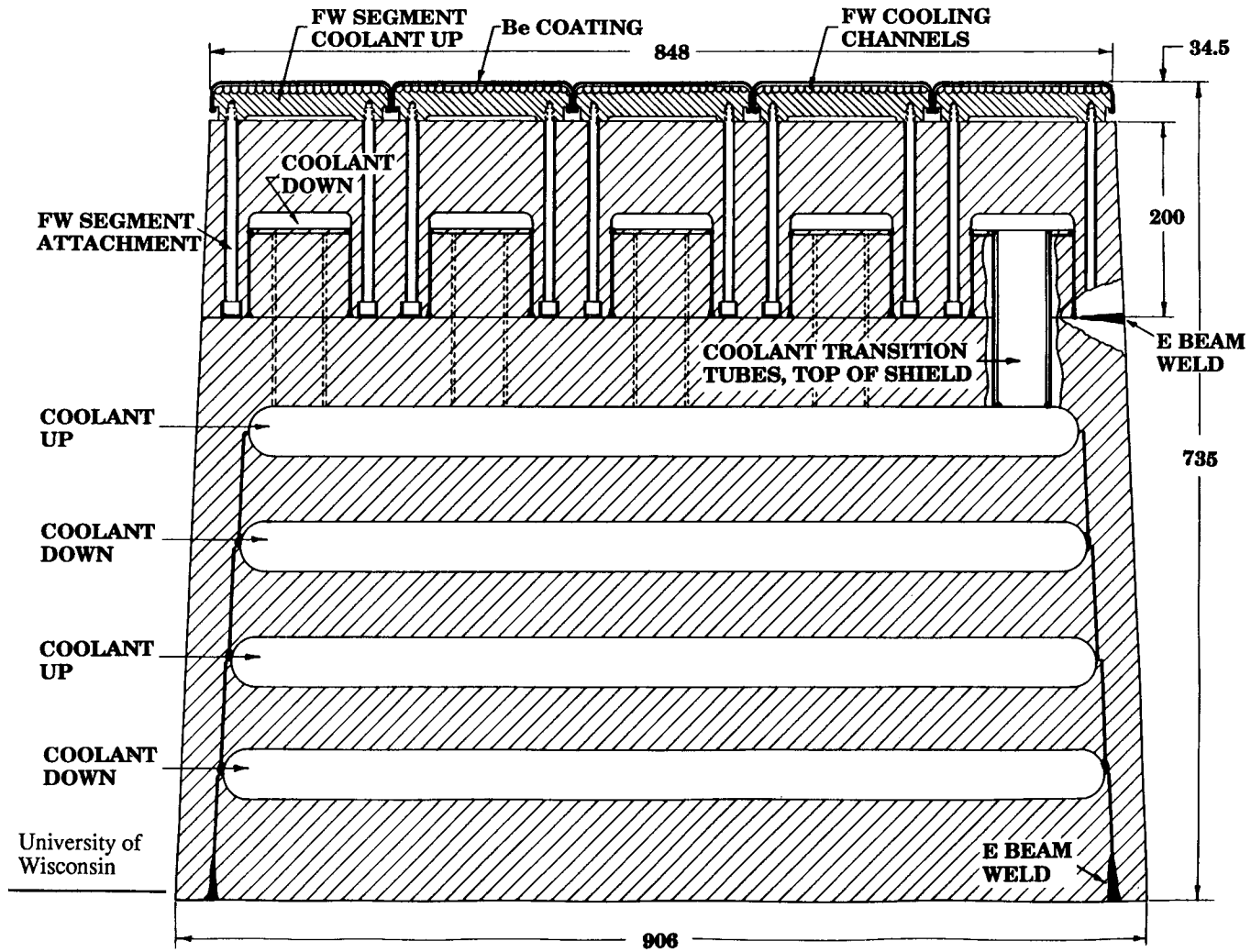
Coolant Selection

- High heat flux on the first wall ($\sim 2.5 \text{ MW/m}^2$).
 - First wall coated with Cu, Be, or W.
 - He: poor heat removal capability.
 - Liquid metal: activation, MHD effects.
 - Water: high pressure, low thermal efficiency.
 - Organic^{*}: low pressure, high thermal efficiency.
- ★ Reduced neutron yield for D-³He cycle reduced radiolytic decomposition and allows organic coolants to be used.

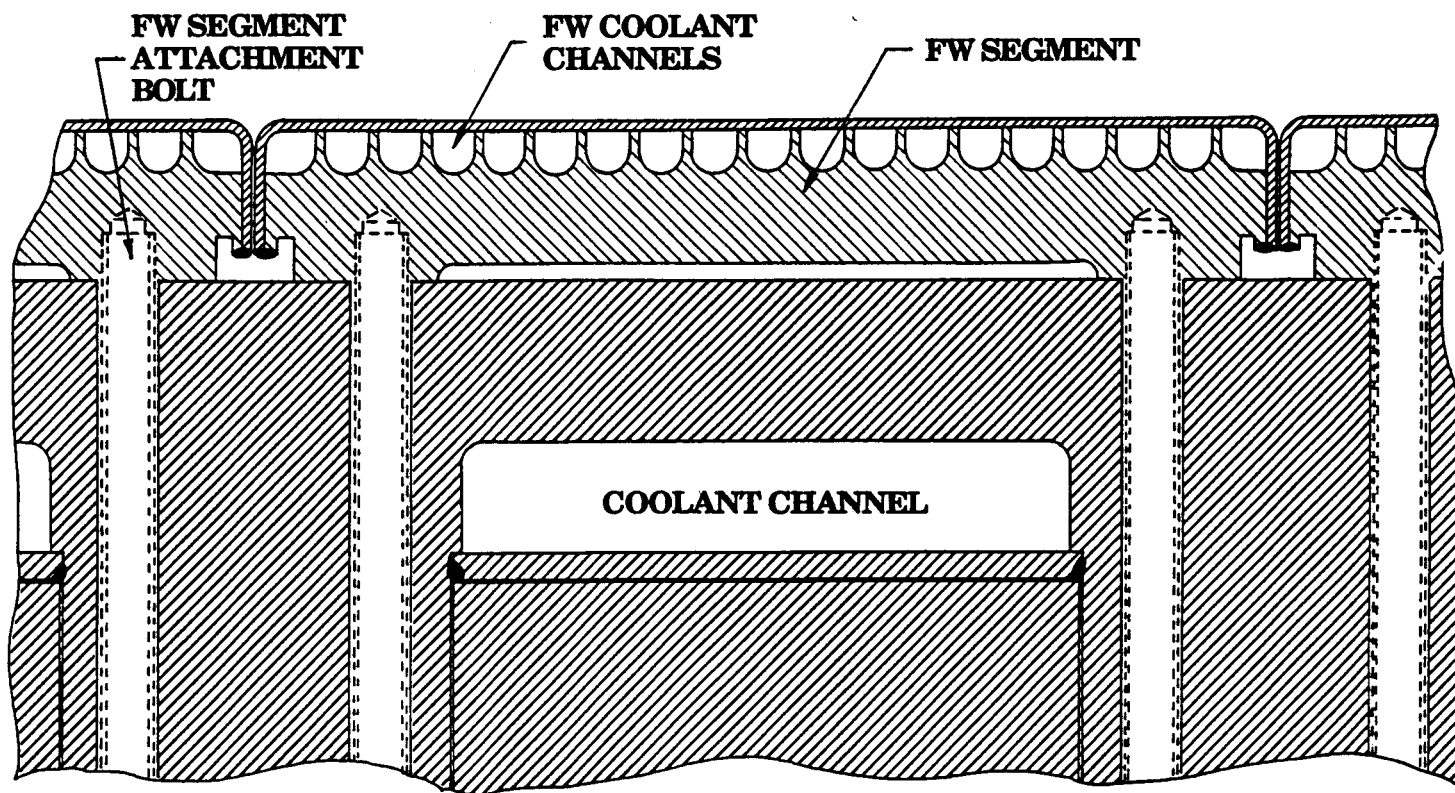
Engineering Features of ARIES-III

- Low activation modified HT-9 is chosen for the shield because it produces the thinnest shield and qualifies as Class-A waste after 30 FPY.
- Modified HT-9 is also used for the first wall.
- First wall is coated by 1.45 mm of Be. Thickness is set to absorb thermal load of one disruption.
- 100 μm of W layer is used in between steel and Be to prevent interaction of Be and steel.
- Steam cycle for thermal conversion ($\eta_{th} \simeq 0.44$).

ARIES-III Fusion Power Core



ARIES-III Fusion Power Core



ARIES-III Major Parameters

Coolant pressure (MPa)	2.6
Inlet temperature (°C)	350
Outlet temperature (°C)	425
Coolant velocity (m/s)	16.5
First-wall thickness (mm)	0.6
Max. first wall temperature (°C)	545
Max. Be temperature (°C)	630
Outboard shield thickness (m)	0.8
Max. Shield temperature (°C)	500

Waste Disposal

- After 30 FPY of operation, shield qualifies as class-A waste after 25 y cool down (WDR of 0.81).

★ Class-C waste after 1 y (WDR=0.06 – 0.19).

- After 7 FPY, divertor armor qualifies as class-A waste.

- After 30 FPY, the total activity in the shield is 1572 MCi at shutdown (5 MW).

896 MCi in one day (1.4 MW).

316 MCi in one year (0.3 MW).

- Production rate of T is 11 g/d. Disposal is an issue.
- Activation of coolant is negligible. Disposal of decomposed coolant is an issue.

ARIES-III LOCA Analysis

- The maximum temperature after a LOCA is 504°C at 3.7 d.
- The maximum temperature after a LOCA with organic coolant fire ($T_{flame} = 1000^{\circ}\text{C}$) in reactor chamber is 600°C.

<u>Temperature</u>	<u>Dose at 1 km</u>
600°C	3.4 rem
800°C	15. rem
1000°C	43. rem

Safety

- Incineration of decomposed coolant causes < 2 mrem/y routine exposure.
- Compared to DT, D-³He fuel results in 1/20 of neutron power, $\sim 1/10$ of afterheat, and 1/4 the activation for comparable structure.
- Activation could be suppressed (use B), but this would increase tritium production.
- Large heat capacity and low afterheat result in a low radioactivity release potential despite activation levels.
- “Worst-case” accident (disruption + LOCA + fire) gives < 200 rem site boundary dose, apparently meeting ESECOM “inherently safe” limits.

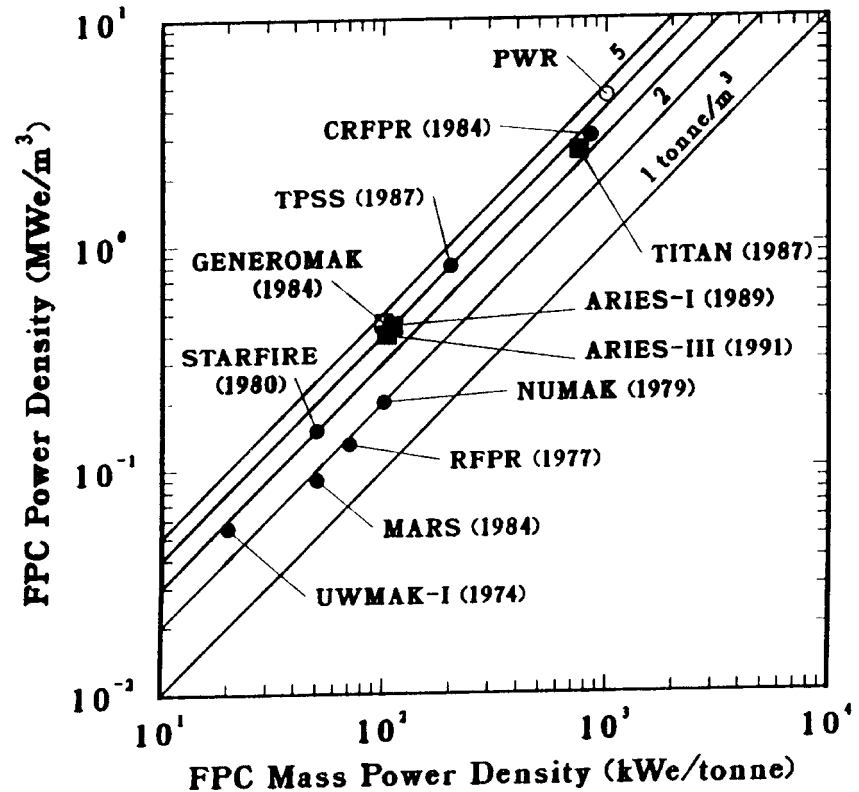
ARIES-I Maintenance

- Complete module replacement (a la ARIES-I) is an option.
- Removal of first-wall and shield modules without moving TF coils is another option.
 - ★ Horizontal maintenance extremely complicated because of coolant headers.
 - ★ Vertical maintenance (a la ITER) appears feasible.
- The choice between two options depends on the failure rate of the TF coils.
- Helical feedback coils are a major maintenance issue.

Economics

COE (mills/kWh)

PWR	65 – 100
ARIES-I	95
ARIES-I (LSA 2)*	81
ARIES-III	93
ARIES-III (LSA 1)*	74



* With safety credits.

Summary

- Design window for power balance appears to be small:

- ★ 1st stability reactor requires:

$$\tau_p^{bulk} / \tau_E^{ash} \sim 1;$$

Efficient current drive;

Direct conversion.

- ★ 2nd stability reactor requires:

$$\tau_p^{bulk} / \tau_E^{ash} \sim 2;$$

Strict profile control;

Thermal conversion;

- 2nd stability reactor is estimated to cost less.

Summary

- ARIES-III reference design is based on 2nd stability with excellent safety and environmental features. COE is comparable to (slightly lower) ARIES-I.
- Use of D-³He fuel resulted in simplification of the shield (no breeding) and magnets located closer to the plasma.
- Lower power density of the plasma and high temperature makes the design very sensitive to physics performance.

QUESTIONS

- Is the ARIES-III design a defensible overall vision of the D-³He tokamak as we present it?
 - ★ How can this vision be made stronger and more defensible?
- Have the potential safety and environmental advantages of D-³He fuel been realized?
- Are there areas or subsystems where you have questions and, if so, what are your recommendations for us?

Key Issues

- The design window for the power balance is small.
- What is a minimum value of τ_p/τ_E without active core ash extraction?
- 2nd stability operation requires a high confinement enhancement multiplier. What is an acceptable limit?
- D-³He tokamak reactors require a highly reflective first wall. The integrity and maintenance of first wall coating are issues.
- Advantages and disadvantages of organic coolants.

DIRECTION FOR ARIES-II

- The ARIES-II design will be based on 2nd stability operation.
 - ★ Lower β and lower temperature may mitigate the strict profile control requirement and eliminate helical feedback coils. However, current drive is required for MHD reasons, independently of whether the reactor is steady state.
 - ★ The confinement enhancement multiplier will still be high because it is based on L/H mode scaling which strongly depends on current.
- What should the principal emphasis of the ARIES-II design be? e.g., should ARIES-II emphasize the best fusion can do (best COE, best safety) or near-term technology, such as metallic structures?