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ABSTRACT

This paper briefly summarizes the key features of Apollo, a conceptual D-^{3}He tokamak reactor for commercial electricity production. The 1000 MWe design utilizes direct conversion of synchrotron radiation power and thermal conversion of transport, neutron, and bremsstrahlung radiation power. The direct conversion method uses rectennas, and the thermal conversion cycle uses an organic coolant. Apollo operates in the first-stability regime, with a major radius of 7.89 m, a peak magnetic field on the toroidal field coils of 19.3 T, a 53 MA plasma current, and a 6.7% β value. The low neutron production of the D-^{3}He fuel cycle greatly reduces the radiation damage rate and allows a full-lifetime first wall and structure made of standard steels with only slight modifications to reduce activation levels. The reduced radioactive inventory and afterheat give significant safety and environmental advantages over D-T reactors.

I. INTRODUCTION

The fundamental question for the D-^{3}He fusion fuel cycle relative to D-T fuel is whether the engineering advantages derived from a low neutron production can overcome the physics disadvantages caused by a lower fusion power density in the plasma. Historically, the anticipated advantages have motivated continued research into D-^{3}He reactors[1] despite the scarcity of ^{3}He on Earth—a difficulty that was solved, in principle, by the identification in 1986 of a major resource of ^{3}He on the lunar surface.[2,3]

For the Apollo study, we chose to quantify the engineering and physics characteristics of D-^{3}He fuel in a tokamak configuration, because of the tokamak's preeminent role in the world's fusion research program. Nevertheless, several alternate concepts—for example, the field-reversed configuration[4] and the tandem mirror[5]—appear to possess even more potential as D-^{3}He reactors, because of their high β values, low magnetic fields, and the relative ease of directly converting fusion power to electricity in them. Numerous papers describing the conceptual D-^{3}He tokamak reactor, Apollo, have been published;[6–14] the present (1992) parameters are listed in Table I.

II. PHYSICS

The Apollo reactor would operate in the "first stability" MHD regime, with plasma parameters chosen to produce a large amount of synchrotron power. The synchrotron power serves two functions: (1) It drives part of the plasma current through toroidally directed absorption of the radiation[15,16] in waveguides, and (2) Rectifying antennas (rectennas) in chambers at the ends of the waveguides directly convert the synchrotron radiation to electricity at high efficiency.[17–19]

The "second stability" MHD regime also has some attractive features, and it was chosen for another conceptual D-^{3}He tokamak reactor design, ARIES-III.[20,21] Some of the factors involved in choosing a stability regime are listed in Table II.[21,22] Although the required first-stablity energy confinement time is closer to the present experimental

TABLE I.

Apollo D-^{3}He Tokamak Reactor Parameters[12,14]

Net electric power	1000	MWe
Fusion power	2144	MW
Synchrotron radiation power	1027	MW
Bremsstrahlung radiation power	652	MW
Transport loss power	456	MW
Neutron power	147	MW
Current drive power	138	MW
Ave. neutron wall load	0.1	MW/m^2
Ave. first wall heat flux	0.84	MW/m^2
Ave. divertor plate heat flux	3.3	MW/m^2
Thermal conversion efficiency	44	%
Direct conversion efficiency	80	%
Net efficiency	43	%
Cost of electricity	77	mills/kWh
Major radius	7.89	m
Aspect ratio	3.15	
Ave. ion temperature	57	keV
Ave. electron temperature	51	keV
Ave. ion density	1.3×10^{20}	m^{-3}
Ave. electron density	1.9×10^{20}	m^{-3}
^{3}He to D density ratio	0.63	
Beta	6.7	%
Troyon coefficient	0.035	
q_ψ	2.67	
ITER-89P H-mode coefficient	4.0	
Plasma current	53	MA
Energy confinement time	16	s
$n_e\tau_E$	29×10^{20}	$m^{-3}s$
$\tau_p^{ash}/\tau_E^{bulk}$	1	
Maximum TF coil field	19.3	T
On-axis magnetic field	10.9	T
Shield thickness	0.68	m
Structural material	Low-activation steel	
First wall coating	Be	
Max. first wall temperature	550	C
Thermal power conversion cycle	Rankine	
Thermal power cycle coolant	Organic	
Power cycle coolant pressure	2	MPa
Waste disposal rating	Class A	

TABLE II.
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

data base, the particle confinement limit is more restrictive—possibly requiring active fusion ash pumping from the core plasma. In both regimes, matching the radial profiles of the bootstrap current and, if used, the synchrotron radiation-driven current to those necessary for MHD stability is critical to limiting the required external current drive power.

The ITER-89P energy confinement scaling relation has been used.[23] For adequate energy confinement in the first-stability regime, this leads to a plasma current of ∼50 MA. Although this value is approximately twice that of the ITER design, Apollo requires no tritium-breeding blanket, so that the first wall and shield can be made robust against the current-quench phase of a disruption. A thermal quench is somewhat more difficult to handle, because the thermal energy content of a D-^{3}He plasma is about five times that of a D-T plasma producing similar fusion power. Thus, the erosion of the first wall and divertor plate during a disruption will be larger. However, a few millimeters of beryllium are sufficient to protect these surfaces, and recent experimental data on vapor-shielding indicate that the erosion will be even lower than originally anticipated.

The energy confinement time required for a D-^{3}He fusion reactor is at least four times the value needed for D-T fuel. The particle confinement time for present experiments is typically 1–10 times the energy confinement time. If the fusion ash confinement time is the same as that of the fuel ions in the plasma, only low values of $\tau_p^{ash}/\tau_E^{bulk}$ ($\lesssim 1.5$ for first stability) are allowed without "choking" the plasma with ash. Because the understanding of energy and particle confinement is still evolving and is a very active research field today, no definitive value of $\tau_p^{ash}/\tau_E^{bulk}$ can be chosen. If high τ_p/τ_E values are found to be characteristic of the reactor regime, active means of "pumping" ash from the fusion core will have to be found.

III. ENGINEERING

The reduced neutron wall load in a D-^{3}He reactor leads to several advantages:

- The radiation damage to the first wall and shield are reduced to levels which allow them to be reactor-lifetime components.
- The radioactive inventory and afterheat are greatly reduced.
- The radiation shield protecting the magnets is typically about one-half of the thickness of the shield in a D-T reactor of similar net power level.
- Currently available structural materials can be used with only slight modifications to reduce activation (modified HT-9 is used).
- The option of using an organic coolant in the thermal power cycle becomes available, because the radiolytic decomposition is manageable.

Furthermore, the elimination of the need for a tritium-breeding blanket greatly simplifies the reactor core design and allows a safer system to be designed.

Having a reactor-lifetime first wall and shield will clearly impact the availability and reliability of a fusion reactor, but such effects are difficult to quantify and, therefore, not assessed in fusion reactor systems studies. Nevertheless, permanent first walls provide a clear, qualitative advantage for D-^{3}He reactors over D-T reactors. In addition, organic coolants, which cannot be used in D-T reactors, are almost as good as water as heat-transfer media, and they can be used at high temperatures (550 C first wall) and low pressures (2 MPa) with good efficiency (44%). Thus, the first wall and shield for a D-^{3}He reactor should be much simpler and more reliable than the first wall, blanket, and shield of a D-T reactor—where high pressure or corrosive working fluids are combined with complex, tritium-breeding blanket geometries.

The high fraction of fusion power produced as charged particles in a D-^{3}He reactor potentially can be directly converted to electricity. In a tokamak, however, we have not found a suitable means of utilizing the best developed method, electrostatic direct conversion.[24,25] Two difficulties arise with this technique: (1) Diverting a magnetic flux tube requires bucking a very high magnetic field, and (2) The scrape-off layer plasma is thermalized at a low temperature, and many stages are required for high conversion efficiency. For Apollo, we have instead chosen conversion of synchrotron radiation power using rectennas.[17–19] The frequencies involved are high, ∼1–30 THz, about three orders of magnitude higher than present microwave rectennas, and vacuum microelectronics components would be required. Nevertheless, the size of components is well within the state of the art for integrated circuits, and the concept could be tested with a modest research program. The presumed benefits in power plant simplicity, reliability, and cost must be balanced against the more difficult physics requirements and the need to demonstrate rectenna technology at the high frequencies of interest.

The first wall of a D-^{3}He tokamak reactor must be highly reflective to synchrotron radiation in order to minimize losses. For Apollo, a beryllium coating was chosen because it does not activate like the main alternatives, copper and tungsten. The wavelengths of synchrotron radiation are very short, so that surface degradation effects are not expected to be important but, because high reflectivity is critical, issues such as radiation effects, redeposition of divertor material vaporized in disruptions, and plasma-surface interactions are important.

IV. SAFETY AND ENVIRONMENT

Because of the low neutron production, the Apollo first wall, shield, and other main structures would qualify for Class A waste disposal. This implies that near-surface burial is possible, even using modified HT-9, a ferritic steel that should be readily available in the 1990's and which is amenable to standard fabrication techniques. The modifications to standard HT-9 consist of reducing Nb, Mo, and Ni.

Approximately 14 g of tritium per day accumulates in the plasma exhaust. This tritium is stored by absorption in titanium getters and is sealed in steel storage containers, each containing 50 g of tritium. These containers have sufficient strength to contain the ^{3}He produced by tritium decay. The maximum stored tritium inventory at the end of the reactor's 40-year lifetime (30 full-power years) will be 59 kg. Tritium decay will generate 19 kW, which will be passively conducted through the vault walls to the natural air sink. This fuel resource will eventually produce 59 kg of ^{3}He.

A loss of coolant accident (LOCA) in Apollo, even with a simultaneous organic coolant fire (flame temperature $\sim$1200 C), has been analyzed to lead to an off-site, whole body early dose to the maximum exposed individual at the reactor site (1 km) of 126 rem. The tungsten divertor will require isotopic tailoring to meet these requirements. The isotopic tailoring appears feasible technically and economically, but it will require processing many tonnes of tungsten. Even under these pessimistic and unlikely assumptions, the dose is less than the 200 rem level—the value recommended by the ESECOM Committee as the threshold for avoidance of early fatalities.[26] Thus, there appears to be no credible way to mobilize sufficient radioactivity to cause any civilian casualities.

V. CONCLUSIONS

The Apollo D-^{3}He tokamak reactor design possesses significant engineering, safety, and environmental advantages over D-T fusion reactors. The main challenges in developing an Apollo reactor lie in the plasma physics and in the rectennas. Notable features of the design include:

- First-stability MHD regime operation,
- Synchrotron radiation current drive and direct conversion using rectennas,
- Thermal conversion using an organic coolant,
- Expected high reliability from increased simplicity and reduced moving parts,
- Modified HT-9, a developed ferritic steel, as the structural material, and
- Very low releasable radioactive inventory from credible accidents.

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