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Abstract

A scoping study of a tokamak reactor fueled by a D-^{3}He plasma is presented. The Apollo D-^{3}He tokamak capitalizes on recent advances in high field magnets (20 T) and utilizes rectennas to convert the synchrotron radiation directly to electricity. The low neutron wall loading (0.1 MW/m^2) permits a first wall lasting the life of the plant and enables the reactor to be classified as inherently safe. The cost of electricity is less than that from a similar power level DT reactor.

Introduction

The technological problems associated with the 14 MeV neutrons and tritium in the D-T fuel cycle are well-known, but this fuel cycle remains the most likely candidate for near term reactors because of its much larger fusion cross section. Nevertheless, the technological problems of D-T fusion are severe enough that advanced fuels may prove superior for longer term power reactors despite their smaller fusion cross sections. D-^{3}He fusion is the most likely advanced fuel candidate because, among advanced fuels, it has the largest fusion reactivity and requires moderate plasma temperatures. The D-^{3}He reaction produces only charged particles which are contained by the magnetic field, but the D-D side reaction produces 2.45 MeV neutrons and tritium, and the D-T side reaction produces 14 MeV neutrons. The fraction of the reactor power associated with neutrons is much less, however, than it is in D-T reactors. Consequently, a D-^{3}He reactor should have significant technological advantages compared with a D-T reactor.

The Apollo study is an investigation of a D-^{3}He fueled tokamak power reactor. Its goal is to assess and quantify the advantages of a D-^{3}He fueled reactor. A preliminary report on Apollo was given in 1988 [1]. In this paper we present an updated view of Apollo. The primary differences are in the physics calculations, where recent results concerning the effect of pressure profiles on the beta limits and of synchrotron power loss are considered. These changes have modified the "optimum" Apollo design point. To distinguish this version from that presented in Reference [1], we designate the version here as Apollo-L2. Further details are given in companion papers [2-5].

Tokamak Design

It is obvious that the design of a commercial D-^{3}He tokamak requires a larger extrapolation of present day physics than does a D-T reactor. The required ion temperature is about 40-60 keV and the $n_e\tau_E$ is about 10^{15} s/cm^3 depending on beta. These parameters are somewhat beyond that for conceptual D-T reactors (ARIES-I has T_i = 20 keV and $n_e\tau_E$ = 2.3 x 10^{14} s/cm^3) [6]. This additional extrapolation is small compared with the tremendous increase in temperature and $n_e\tau_E$ in the last decade. Although other magnetic configurations are better suited to the particular characteristics of advanced fuels, the tokamak configuration was chosen for the Apollo study since it represents the world's current leading confinement concept in terms of plasma parameters achieved.

Low beta, small aspect ratio, and first stability operation was chosen for Apollo since it represents the current data base, but a second stability reactor with higher beta and high aspect ratio would also be an attractive choice. The constraints placed on the Apollo study were an electrical output power of 1200 MW$_e$ in order to compare with the ESECOM [7] study, a neutron wall load no greater than 0.1 MW/m^2 in order to have a first wall that lasts the full reactor lifetime of 30 full power years, and a maximum magnetic field at the toroidal field magnets less than 24 T.

Apollo operates at high plasma temperature and high magnetic field; consequently, synchrotron radiation is an important loss mechanism. Direct conversion to electricity of synchrotron radiation along with the option of thermal conversion was evaluated.

Apollo-L2 General Description

Key parameters of the Apollo-L2 reactor and its variants are given in Table 1. A maximum TF coil field of 20 T (see Ref. 1 for a justification of this value) is used. In the first case (A), where synchrotron radiation is being converted directly to electricity while the remaining thermal energy goes through a steam cycle to produce electricity, the overall net electrical conversion efficiency is 54%. This stems from the fact that 44% of the energy is being converted at 80% efficiency and the other 56% is being converted at 40%. The levelized cost of electricity (COE) is 44 mills per kWh at 75% capacity factor (CF).

Table 1. Key Parameters of Apollo-L2

PARAMETER	A	B	C	D
Energy Conv. (*)	M	S	T	M
B_{max} (T)	20	20	20	20
B_{Plasma} (T)	9.5	9.75	9.74	10.6
Plasma Current (MA)	70	80	79.4	60.7
Beta (%)	9.3	9.3	9.3	7.8
Ion Temp. (keV)	51.4	70.7	51.0	51.4
τ_E (s)	22	23	29	23
$n_e\tau_E$ (10^{14} s/cm^3)	50	41	71	54
Aspect Ratio	2.5	2.5	2.5	2.85
Major Radius (m)	6.4	7.1	7.1	6.8
Fusion Power (MW)	2110	2807	3122	2109
Net Efficiency (%)	54	41	37	54
Synch. Power (MW)	989	1663	1496	1001
Bremsstrahlung (MW)	852	790	1347	859
Divertor Power (MW)	207	267	225	193
D-D Neut. Power (MW)	24.6	36.5	37.1	24.4
D-T Neut. Power (MW)	86.4	102	105.1	85.3
FW Heat Load (W/cm^2)	86	67	107	87
Direct Costs (B$)	1.36	1.39	1.42	1.38
Capital Cost ($/kWe)	1133	1157	1180	1148
Availability (%)	75	85	75	75
COE (mills/kWh)	43.5	40.8	49.7	43.7

(*) M = Mixed synchrotron and thermal conversion
S = Synchrotron conversion only
T = Thermal conversion only

Three variations of the first case were considered. Case B shows the effect of maximizing the synchrotron radiation and disposing of the bremsstrahlung, divertor, and neutron power directly to the cooling tower. This resulted in a bigger plasma (R=7.1 m vs. 6.4 m) and a larger plasma current (80 vs. 70 MA). The total neutron power also increased from 111 to 138 MW and the overall efficiency dropped to 41%. Table 1 also shows that the capital costs of the two different conversion cycles are roughly equal but the COE of B is less because the solid-state rectenna conversion of microwaves should be more reliable than high temperature-high pressure power cycles with turbines.

The second variation, C, considers purely thermal conversion at 40% efficiency, including the synchrotron power. This is a fallback case if the rectenna technology for direct conversion of synchrotron power to electricity does not prove to be feasible. The COE for this case is about 20% above the pure microwave conversion case, but is still competitive with similar sized D-T power reactors.

Finally, case D shows the effect of increasing the aspect ratio to 2.85 in order to lower the current to 61 MA. It is not possible to go to higher aspect ratio without changing

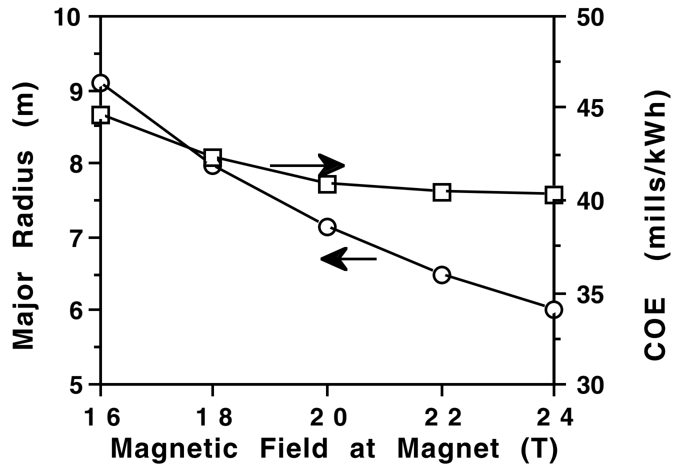

Fig. 1. Major radius and cost of electricity versus magnetic field strength at the magnet.

the physics rules, because beta decreases as the aspect ratio increases, and synchrotron radiation becomes more severe at lower beta. Consequently maintaining a power balance on the plasma becomes harder and the plasma Q degrades.

The base case for the rest of this paper is case B with synchrotron conversion only.

The physics model in reference [2] was used to determine the parameters for the four cases given in Table 1. Shown in Fig. 1 is the major radius and COE versus the magnetic field strength at the magnet. We see a considerable reduction in size and COE as the magnetic field strength is raised. This variation is done using case B in Table 1 as the base and varying the magnetic field strength while keeping the aspect ratio, electrical power output, and neutron wall loading constant. The cost of electricity shows about a 10% cost reduction when raising the magnetic field at the magnet from 16 T to 20 T.

Technology Considerations

When assessing the Apollo-L2 reactor design one finds that there are three technological features which need to be discussed. These are: heat flux on first wall and divertor plates, direct converter rectenna, and radiation damage.

Heat Flux Considerations

Table 1 reveals that, in the base case, approximately 70 W/cm^2 must be handled at the first wall. This value is similar to, or less than, that for D-T power reactors. This is due to the larger surface area in D-^{3}He systems. The average heat on the divertor plates is on the order of 300 W/cm^2. It is obvious that these values are not unusual compared to other tokamak or RFP designs and should be well within the technology base within the next 10 years.

Rectenna Technology

The use of solid-state rectifying antennas (rectennas) to convert synchrotron radiation directly to electricity at high efficiency appears to be an attractive option [8]. The synchrotron radiation would be carried by overmoded waveguides to chambers with rectennas tuned to a selected harmonic. The conversion concept is to use 0.1 mm-wave dipole antennas and an electronic circuit utilizing a field-emission diode with a fast response time. Fabrication of the rectennas would require the technology of very large scale integrated circuits (VLSI) and, although the dimensions involved are well within the limits of present VLSI experience, the specific techniques needed for large scale production need to be demonstrated.

Radiation Damage to Structural Materials

The low neutron wall loading results in approximately 3 MW-y/m^2 of damage in 30 FPY's. Because one can operate the Apollo structure at relatively low temperatures, helium embrittlement effects typical of high temperature D-T operation are not present. Consequently, the first wall should last the full lifetime of the plant.

Economic Analysis

At this early stage of D-^{3}He reactor designs one can only view cost analyses as general trend indicators and not definitive numbers. Nevertheless such cost considerations do highlight areas of advantage while, at the same time pinpointing areas for improvement. The Generomak [9] cost code was used to be able to compare to the ESECOM [7] study of D-T power reactors.

The results of the economic analysis of the four cases (A-D) in Table 1 are given in Table 2. Case B, which uses only direct conversion of synchrotron radiation to electricity and dumps the thermal energy to a cooling tower, has the lowest (41 mills/kWh) cost of electricity. Case C, in which the fusion power is converted to electricity using a 40% efficiency thermal cycle, has the highest COE (50 mills/kWh). Cases A and D, which use a combined system of direct conversion of synchrotron radiation and thermal conversion of the rest of the fusion power, has a COE about 5% more than case B. This is partly because of the cost of the additional components needed for case A and partly because a higher availability has been assumed for case B. The solid-state rectenna units should not be subject to as frequent failure rates as high pressure steam systems. In addition, the first wall and shield can run at lower temperatures in case B. Because the turbine and high temperature heat transport part of a power plant typically contributes about 10% to the reduction in the availability, we have chosen 85% as the value for case B and 75% for the other cases.

Table 2. Key Economic Factors for Apollo-L2 Design

Costs-M$ (1986)	A	B	C	D
Magnets	181	251	246	205
Reactor Components	141	158	182	139
Reactor Building	270	253	298	267
Turbine Plant and Direct Conversion	383	448	251	385
Electric Plant	147	74	72	147
Other Reactor Plant Equipment	117	141	217	116
Heat Transfer	83	34	113	82
Miscellaneous	37	29	37	37
Total Direct Cost	1359	1388	1416	1378
Indirect Cost	407	416	424	413
Contingency	265	271	276	269
Overnight Cost	2031	2075	2116	2060
COE-mills/kWh	43.5	40.8	49.7	43.7

A comparison of the Apollo-L2 design with partial nuclear grade construction costs to the base D-T case (V/Li) of the ESECOM study is given in Fig. 2. Both direct capital cost values are exclusive of any contingency values. The lack of a breeding blanket makes the Apollo nuclear island costs (minus the magnets) about half of ESECOM. Large reductions in the heat transfer costs (i.e., heat exchangers, large high pressure, high temperature pipes, etc.) are achieved by the Apollo design. Finally, the allowance of partial nuclear grade construction also results in significant savings for the Apollo design. Overall, the cost of electricity from Apollo is more than 25% lower than from a D-T tokamak (i.e., 41 vs. 53 mills/kWh). The cost of fuel for the Apollo-L2 reactor series was assumed to be 1000$/g, roughly 10 times that assumed in the ESECOM [7] study. The projected cost of He-3 from the moon is consistent with an extensive study at the University of Wisconsin [10].

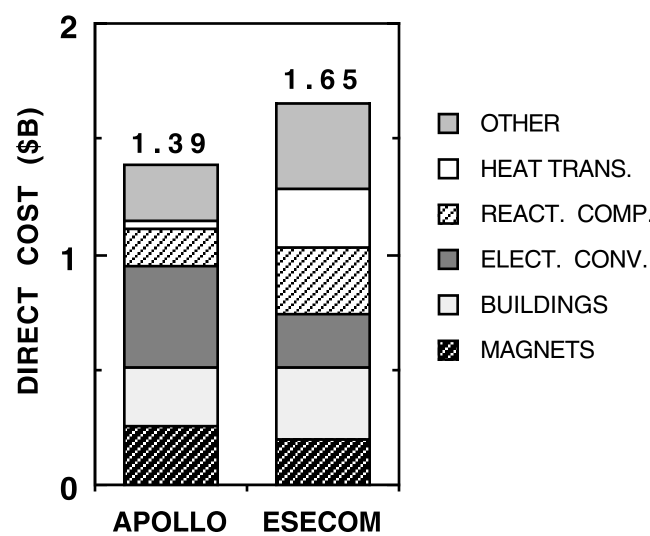

Fig. 2. Comparison of the direct capital costs of two 1200 MWe tokamak designs.

Safety and Environmental Factors

There are 3 main areas where the D-^{3}He Apollo power plant has very attractive safety and environmental features compared to D-T fusion power plants. These are: low level radioactive wastes after decommissioning, inherent safety due to extremely low decay heat, and extremely low tritium inventory.

The high manganese austenitic stainless steel, Tenelon, has been chosen for the first wall, vacuum vessel, and shield. Neutronics and radioactivity calculations were used to determine the total radioactivity as a function of operating life and time after shutdown. The waste disposal rating for Class C waste is given in Table 3. The main conclusion that one can draw from these calculations is that after a full reactor lifetime the Apollo-L2 structure can be disposed of as low level waste by shallow land burial. The material easily qualified for Class C and, in fact, can qualify for Class A.

Table 3. Class C Waste Disposal Rating After 30 FPY's of Operation

Inboard Shield Alone	0.034
Outboard Shield Alone	0.023
Inboard + Outboard	0.026

The worst possible accident that can usually be envisioned for a fusion reactor with respect to controlling decay heat is to instantly lose the coolant while the plasma remains on. A time dependent LOCA calculation for the shield was done using the ATHENA code for Apollo. The calculations assume the TF coils to act as heat sink. The results show that two weeks after LOCA, the maximum first wall temperature levels off at about 200°C [3].

Table 4. Key Tritium Parameters

Production Rate	Tritium, g
Born in Plasma	40.2/d
Burned in Plasma	19.5/d
Exhaust from Plasma Chamber	20.7/d
End of Life Inventory	
First Wall + Tiles	0.01
Divertor Plates	1.5
Coolant Water (Shield + FW)	0.001
Divertor Coolant Water	1.0
Plasma Exhaust and Reprocessing	3.5

Total	6

Although tritium is not a fuel constituent, it becomes an integral part of the fuel reprocessing system because it is produced as a result of D-D reactions and is consumed by D-T reactions in the plasma. Table 4 shows an estimate of the tritium inventory in the various reactor components. The inventory of tritium in all the reactor components is small and insignificant compared to a D-T reactor system of comparable power. The prudent disposition of the nearly 21 g/d of tritium removed from the exhaust fuel system requires further study. One possibility is to store the tritium in uranium getter beds and let it decay to ^{3}He. In this case the steady state inventory of the stored tritium is 134 kg. Using TSTA costs, the storage beds would cost about $13 million.

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