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Abstract

The Apollo-L3 conceptual reactor design utilizes D-^{3}He fuel in a first stability tokamak configuration with direct conversion of synchrotron radiation to electricity as well as thermal conversion of surface heat and neutron energy. In this paper we present an update of the parameters of the design and report on analyses of certain critical issues of Apollo-L3. These include plasma startup, loss of fast ions by magnetic ripple, safety analyses, and tritium storage.

Introduction

The Apollo study is an investigation of D-^{3}He tokamak fusion reactors with the goal of finding a way to take advantage of the technological advantages of the D-^{3}He fuel cycle compared with the D-T fuel cycle, while minimizing the extrapolation of plasma physics requirements beyond those required for a D-T tokamak reactor. The technological advantages include a factor of 10-50 reduction in 14 MeV neutron production and associated radiation damage and activation of the structure, a similar reduction in the radioactive waste disposal problem, elimination of the need for tritium breeding, elimination of the need for periodic replacement of the first wall, and the possibility of direct conversion for higher overall system efficiency.

The plasma physics requirements are more demanding because of the lower fusion cross-section for the ^{3}He(d,p)^{4}He reaction. This results in about a factor of 4 increase in the nτ for ignition and a factor of 2-3 increase in the plasma operating temperature. The higher operating temperature causes synchrotron radiation to be a larger fraction of the total power loss than in D-T plasmas. The need for a larger nτ also increases the ash accumulation in the plasma. The ratio of the particle confinement time to the energy confinement time becomes an important parameter. Practical solutions to the power and particle balance equations have not been found for ratios larger than about 1-1.5 for the first MHD stability regime and about 2-3 for second stability.

Three reactor designs (Apollo-L [1], Apollo-L2 [2], and Apollo-L3 [3]) have been issued. All three are first stability tokamaks utilizing direct conversion of synchrotron radiation to electricity. In Apollo-L and Apollo-L2 the thermal heating of the divertor, first wall, and shield was discarded and not converted to electricity. In Apollo-L3, a thermal cycle is used in addition to direct conversion of the synchrotron radiation in order to minimize the fusion power required to achieve a given net electric power. In this paper we present an update of the parameters of Apollo-L3 and discuss in more detail some of the critical issues confronting this design.

Updated Design Parameters

Apollo-L3 is a first stability tokamak utilizing direct conversion of synchrotron radiation to electricity as well as thermal conversion of surface heating and neutron power. It also utilizes synchrotron current drive in conjunction with neutral beam current drive to achieve steady-state operation. The updated parameters for the reference Apollo-L3 design are given in Table 1. Column A shows the parameters from Ref. 3 for comparison purposes. Column B shows the updated parameters. The reasons for the change in the parameters are improvements in the physics modelling, especially ion transport and synchrotron current drive. The net results are an increase in the major radius of about 40 cm and an increase in the current drive power of about 40 MW. The total plasma current is 53 MA; this is composed of 23 MA of bootstrap current, and 18 MA driven by the synchrotron radiation, and 12 MA by neutral beam injection (138 MW). Also shown in Table 1 (column C) is a case utilizing synchroton current drive, but direct conversion is not utilized. The synchrotron radiation is converted to electricity by means of the thermal cycle, along with the surface heat and neutron power. This case is a backup option if direct energy conversion of synchrotron radiation turns out to be infeasible; the impact on the COE is a 10% increase.

Table 1. Key Parameters of Apollo

Parameter	A[1]	B[2]	C[3]
Energy Conversion	mixed	mixed	thermal
Aspect Ratio	3.15	3.15	3.15
Major Radius (m)	7.47	7.89	8.37
Max. Field @ TF Coil (T)	19.3	19.3	19.3
Magnetic Field on Axis (T)	10.9	10.9	11.1
Avg. Electron Dens. (10^{20} m^{-3})	1.92	1.87	1.94
Avg. Ion Temp. (keV)	58	57	57
Beta (%)	6.7	6.7	6.7
Troyon Coefficient	.035	.035	.035
Plasma Current (MA)	49.3	53.3	57.2
q_ψ	2.67	2.67	2.67
Energy Conf. Time (s)	13	15.5	17.4
ITER-P H-mode coeff.	3.5	4	4
$n_e\tau_E$ (10^{14} s/cm^3)	25	29	34
Fusion Power (MW)	1923	2144	2602
Synchrotron Power (MW)	940	1027	1249
Bremsstrahlung (MW)	518	652	858
Transport Power (MW)	436	456	497
D-D Neutron Power (MW)	29	38	40
D-T Neutron Power (MW)	96	109	116
Avg. n Wall Load (MW/m^2)	0.1	0.1	0.1
Avg. FW Heat Flux (W/cm^2)	87	84	101
Current Drive Power (MW)	96	138	157
Direct Conv. Eff. (%)	80	80	–
Thermal Conv. Eff. (%)	44	44	44
Net Electric Power (MW)	1000	1000	1000
Net Efficiency (%)	47	43	36
COE (mills/kWh)	69	77	84

[1]Parameters from Reference 3.
[2]Updated parameters for Apollo-L3.
[3]Thermal conversion only variation.

Plasma Startup

Plasma startup of Apollo-L3 can be studied using POPCON analysis; a POPCON plot is shown in Fig. 1. In order to reach the operating density and temperature shown in Table 1, auxiliary heating is needed; the path requiring the minimum heating power is one which passes through the saddle point in Fig. 1 at a temperature of 40 keV and a fuel density of about 0.95×10^{20} m^{-3}. This path requires a total auxiliary heating power (including current drive) of about 260 MW. Since the current drive system can only provide 140 MW, an additional 120 MW of some form of heating is required. Rather than provide this through external heating, it can be provided by seeding the plasma with a small amount of tritium and taking

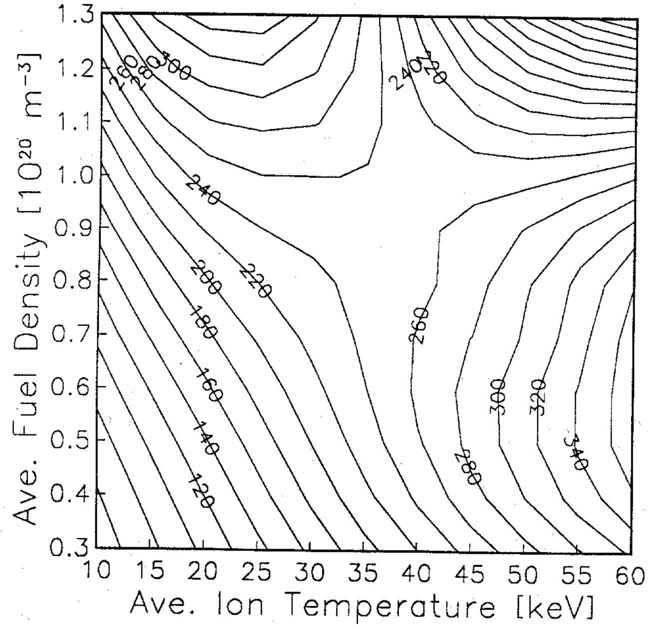

Fig. 1. Contours of injection power for pure D-^{3}He startup.

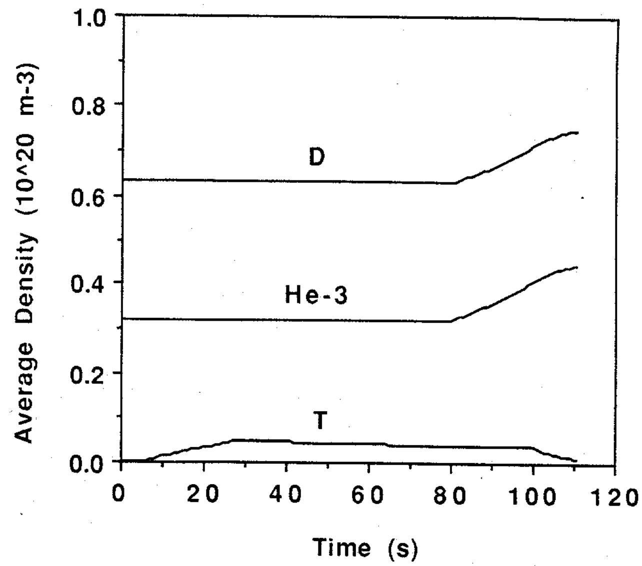

Fig. 2. Average fuel density versus time for D-T assisted startup.

advantage of the larger D-T cross-section at low temperature.

Shown in Fig. 2 and 3 is the result of a time-dependent simulation using tritium to assist the startup process. The plasma startup begins with a D-^{3}He plasma at a density of 0.9×10^{20} m^{-3} and a temperature of 1 keV. With 138 MW of neutral beam heating, the ion temperature starts to rise. When the temperature reaches 5 keV, tritium injection is started. The peak tritium concentration is about 5% and is reached when the temperature reached 10 keV. This produces sufficient alpha heating to cause the plasma to pass through the saddle point in Fig. 1. Once the plasma reaches 52 keV, tritium fueling is turned off and the tritium concentration decays by transport across the magnetic field and burnup. At the end of the simulation shown, the plasma is at the desired operating density and temperature; the tritium concentration is about 0.75% and decaying rapidly to the steady-state value of 0.24%.

Injection of tritium produces a pulse of D-T neutrons, as shown in Fig. 3. The total energy released in these 14 MeV neutrons is 67 GJ. A similar startup scenario was analyzed for ARIES-III [4] and produced a somewhat larger neutron pulse; thermal hydraulics calculations showed that the temperature rise in the shield was within design limits. With this startup scenario, the neutral beam heating provided by the neutral beam current drive is sufficient to bring the plasma to the desired operating point so that no additional heating capability is required.

Loss of Fast Ions Due to Magnetic Ripple

The loss of fusion-product protons and alpha particles can contribute significantly to the total energy loss from the plasma. D-^{3}He plasmas are more vulnerable to magnetic ripple loss than are D-T plasmas because of the larger gyroradius of the 14.7 MeV protons compared with the 3.5 MeV alpha particles. The dominant ripple loss mechanism appears to be stochastic ripple loss; this has been analyzed using the RIPLOS code [5]. For the present estimate of loss rates, a version of RIPLOS which only treats circular magnetic flux tubes was used. For the ripple model, we used a 16 coil ITER case provided by White [6] and scaled the ripple to the Apollo major and minor radii. We scaled to a circular flux tube by dividing the coordinate in the vertical direction by the elongation at the 95% flux surface. The RIPLOS results for proton and alpha particle loss are shown in Fig. 4, where some scatter appears due to statistical effects. Both stochastic ripple loss and prompt (first orbit) loss are included in the total loss shown. For a vacuum ripple of 1-2%, the fast ion particle loss is about 1%; this has a negligible effect on the plasma power balance. Neglected in this analysis is the ferromagnetic nature of the ferritic steel shield; this is expected to reduce the magnetic ripple even further. Consequently, fast ion loss due to magnetic ripple is not expected to be a significant concern in Apollo.

Safety and Environment

Release of radioactive isotopes into the environment during an accident situation is a concern for all fusion reactors. The maximum temperature reached by the activation products generated in the reactor structure is determined by the amount of energy available at the onset of an accident. In Reference 3, it was reported that the temperature of the ferritic steel (modifed HT-9) structure first decays at the onset of a loss of coolant accident and then rises to a maximum of 500°C after about one week. The temperature the structure reaches in an accident determines the release fraction of the activation products, which, in turn, determines the offsite dose produced by the accidental release of the activation products.

Since mobilizing all of the radioactive products is quite unlikely, offsite dose calculations were done using the experimental volatility rates [7] of the different radioactive nuclides in the structure as a function of the shield temperature during a loss of coolant accident. Even though the highest temperature the structure reaches is 500°C, the volatility rates used in this calculation were those given for 600°C for HT-9 in dry air. To estimate the release fractions for each radioisotope, we assumed a 10 hour duration of the LOCA in which the 1-hour release rates are used for the full 10 hour duration; this allows for any possible loss of oxide protection. Another conservative assumption made in the calculation was to assume an average sheet thickness of 2 mm, which is the thickness of the first wall of the reactor.

Our results show that the Apollo-L3 structure produces a whole body early dose of only 3.6 rem, which is less than the 5 rem level where evacuation plans need to be considered. Most of the early offsite dose is produced by manganese and tungsten isotopes; ^{54}Mn and ^{56}Mn produced from iron and manganese in modified HT-9 produce about 70% of the potential dose. ^{187}W, which is produced from ^{186}W, produces 25% of the dose.

Another set of offsite dose calculations were performed assuming the structure reached a temperature of 1200°C; this is the estimated structure temperature during an accident in which the total volume of the or-

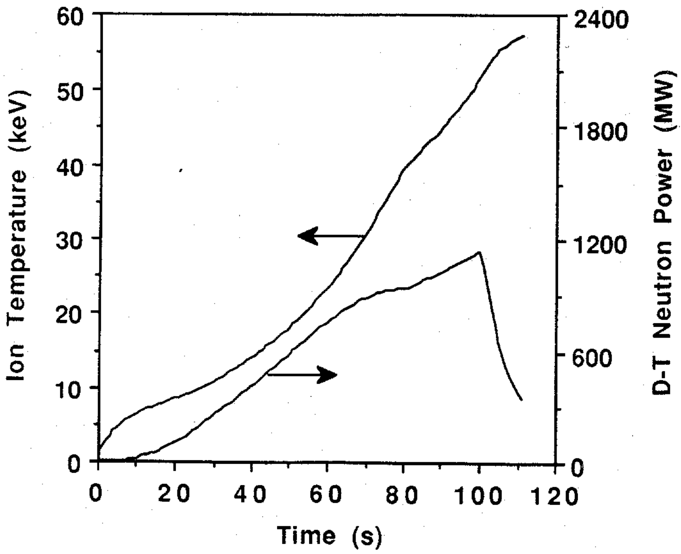

Fig. 3. Rise of the ion and electron temperature during startup and the 14 MeV neutron power produced by the tritium seeding.

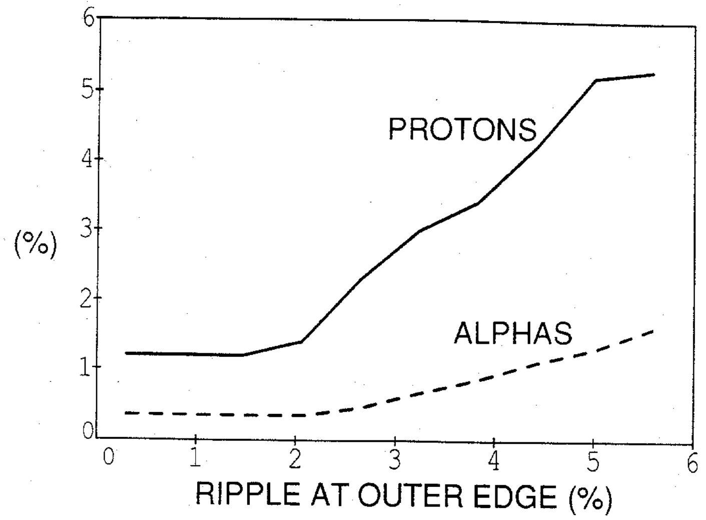

Fig. 4. Particle loss rate due to magnetic ripple.

ganic coolant is burning inside the plasma chamber under adiabatic conditions. We also assumed a loss of coolant accident during the organic coolant fire to allow for including the decay heat as an extra energy source. For this accident scenario, the early offsite dose was calculated to be 103 rem, which is below the 200 rem prompt dose limit adopted by the ESECOM [8] study as a threshold for avoidance of early fatalities in the case of accidental release of the radioactive inventory.

According to the ESECOM definition of level of safety assurance (LSA), an Apollo-L3 low activation ferritic steel structure could qualify for an LSA rating of one. This LSA rating is achieved on the basis of inventory since the highest temperature the structure would reach following a LOCA ranges between 400°C and 500°C. The analysis showed that the offsite early doses are 3.6 rem for a modified HT-9 structure at 600°C and 103 rem at 1200°C.

Tritium Storage

Approximately 13.6 g/day of unburned tritium is accumulated in the plasma exhaust system. This tritium is stored rather than returned to the plasma fuelling system. This is to avoid increasing the 14 MeV neutron production in the plasma. The tritium is absorbed in titanium getters and sealed in steel storage containers, each containing 50 g of tritium. The sealed storage containers have sufficient strength to contain the ^{3}He formed from the decay of the tritium. These containers are stored in a suitable vault isolated from the reactor building. Without recycle nearly 3000 containers will be accumulated by the end-of-reactor life (40 yr) and contain about 59 kg of tritium. The maximum heat generated by the tritium decay, 19 kW, is passively conducted through the vault walls to a naturally occurring air-sink. The capital, operation, and maintenance costs for such a storage system are estimated to be $285 per gram of tritium. This is a passively safe system which requires no surveillance, but should be located in an exclusion area for about 140 years.

The decay of tritium produces ^{3}He which is valuable as the plasma fuel. An alternative procedure is to routinely remove the ^{3}He produced from tritium decay for use and inject it into the plasma. If the ^{3}He were removed every 12.3 years (one tritium half-life), the vault would contain 1960 containers at end-of-life and only 50 containers after 100 years. This procedure produces ^{3}He at a cost of $425 per gram, which is much less than the cost of ^{3}He from any other source.

Summary

The parameters of Apollo-L3 have been updated to reflect changes in the physics modelling. This has led to an increase in the major radius by about 40 cm and an increase in the COE by about 10%. An alternative to direct energy conversion of the synchrotron radiation is to convert the energy using a thermal cycle; this increases the cost by another 10%. The reference case for Apollo-L3 continues to use direct conversion. Startup of the plasma using a small amount of tritium eliminates the need for auxiliary heating other than that provided by the current drive system.

Analysis of accident scenarios lead to a possible offsite early dose of 3.6 rem for a LOCA without burning of the organic coolant and 103 rem if the organic coolant burns. On the basis of the expected temperature of the shield in a LOCA accident and the radioactive inventory, Apollo-L3 qualifies for a LSA rating of one. Storage of the tritium produced in the plasma avoids the increase in 14 MeV neutron production caused by re-injecting the tritium into the plasma and, if the ^{3}He produced from tritium decay is recycled, produces ^{3}He fuel at a cost of about $425 per gram.

Acknowledgments

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