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Presented at the 9th Topical Meeting on the Technology of Fusion Energy, 7–11 October 1990, Oak Brook IL; *Fusion Technology* **19** (1991) 791.

FUSION TECHNOLOGY INSTITUTE

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APOLLO-L3, AN ADVANCED FUEL FUSION POWER REACTOR UTILIZING DIRECT AND THERMAL ENERGY CONVERSION

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ABSTRACT

The design of a 1000 MWe D-He3 tokamak fusion power plant, Apollo-L3, is presented. The reactor operates in the first plasma stability regime and relies on both direct and thermal conversion of the thermonuclear energy to electricity. The synchrotron energy is converted directly to electricity via rectennas at 80% efficiency and the thermal energy is converted through an organic coolant at 44% efficiency. It is designed with a low neutron wall loading (0.1 MW/m^2) which allow a permanent first wall to be used. The overall net efficiency is 47%. A low level of induced radioactivity and the low afterheat in the reactor allows the low activation ferritic steel waste to be treated as Class A and the system to be considered as a Level 1 (Inherently Safe) device. The cost of electricity (COE) is 69 mills/kWh making it competitive with recent advanced DT reactor designs.

INTRODUCTION

For over 20 years the fusion community has tried to design a tokamak fusion power plant which could generate electricity safely, with minimum environmental impact, and at a cost which is competitive with fission and coal plants of the 21st century. Over 40 major designs have been published[1] and a great deal of progress has been made. However, one major drawback of the past efforts has been the use of the deuterium (D) - tritium (T) fuel cycle. Since 80% of the DT fusion energy is in 14 MeV neutrons, most of the engineering problems encountered thus far have been connected with attempts to minimize the harmful effects of radiation damage by neutrons and with ways to cope with the neutron induced radioactivity in the structure around the plasma. In addition, the production and safe handling of tritium has presented major design challenges to the fusion community.

One way to mitigate the problems stated above is to utilize a fuel cycle which emits a far lower fraction of its thermonuclear energy as neutrons and does not require the use of a radioactive fuel. Such a reaction has been known for over 30 years and that is the D-He3 cycle:

$$D + {}^3He \rightarrow p + {}^4He + 18.4\ MeV\ .$$

Unfortunately, until 1986 it was thought that there was no large supply of the ^3He isotope readily available for a commercial power industry. In 1986, scientists at the University of Wisconsin showed that there is an enormous supply of ^3He on the lunar surface.[2] Using data generated from the U.S. Apollo landings, it was discovered that over 1 million tonnes of ^3He are present on the lunar surface and that resource is equivalent to 20 billion megawatt years of energy (the present worldwide energy consumption is ≈0.01 billion megawatt years per year). Since only a few percent of the thermonuclear energy released in the D-He3 reaction is in neutrons, and the fuel is entirely non-radioactive, there are significant safety, environmental, and economic advantages of the D-He3 cycle over DT.

The main disadvantage of the D-He3 cycle compared to the DT cycle is the higher temperature required for reactor operation (≈3 times) and the larger $n\tau$ values needed (≈5 times; about 7 times in a high synchrotron radiation fraction mode).[3-5] Such requirements would normally translate into a much larger tokamak except that the lack of a tritium breeding blanket and lower neutron fraction results in much less structure between the plasma and the magnets.[6] The ability to convert the charged particle energy directly to electricity at 60-80% efficiencies reduces the amount of fusion power needed to generate the same net power. This is more important in linear systems like tandem mirrors but it can also increase the overall efficiency of tokamaks. The end result is that D-He3 tokamaks are only slightly larger in size (≈20% in major radius) than DT reactors of comparable power level.[7]

The object of this paper is to compare the latest in the Wisconsin Apollo series of D-He3 tokamaks to the latest DT tokamak design (ARIES-I).[7] Previous designs, Apollo-L,[3] and Apollo-L2,[4] have utilized direct conversion alone whereas the present design employs a mixed mode energy conversion scheme which utilizes *both* direct and thermal conversion.

GENERAL REACTOR DESIGN PHILOSOPHY

One of the first decisions to be made in tokamak reactor design is the operating beta stability regime. Present experimental facilities operate in the so-called first stability regime characterized by relatively low betas (≈6-10%) and low to moderate aspect ratios.[3-5] Essentially all the previous tokamak designs over the past 20 years have been in that regime.[1] More recently, it has been speculated that one might be able to operate in a higher beta stable regime, called second stability, where the beta values might be in the 10-25% range.[8] However, this operating regime has not yet been achieved experimentally and our remarks will be limited to the first stability regime only.

The key features of the first stability plasma operating regime are listed below in Table 1.

Table 1. Considerations for first vs. second stability plasma regime in D-He3 tokamaks.

<u>Main Advantages of First Stability Regime</u>

- Builds on current world plasma database.
- High synchrotron fraction.

<u>Main Disadvantages of First Stability Regime</u>

- High plasma current.
- May need active ash removal.

The low beta system builds on a large body of worldwide physics information but results in relatively high plasma currents which could be a problem if a disruption occurs or if synchrotron/bootstrap current drive mechanisms are not available. The high fraction of energy released as synchrotron radiation in a D-He3 tokamak makes synchrotron current drive and direct conversion more attractive. On the other hand, the long confinement times required may mean that an active method of proton and helium-4 "ash" removal is required.

In order to compare to the most recent DT tokamak design, ARIES-I,[7] it was necessary to choose a 1000 MWe power level. Other constraints that were imposed on the Apollo-L3 design include:

- Maximum magnetic field at the TF coil <22 T.
- Permanent first wall (neutron wall loading <0.1 MW/m^2).
- Plasma current <50 MA.
- Particle confinement time/energy confinement time ≥ 1.
- Class A long term waste.
- Level 1 - Inherently Safe Operation Mode.

The limit on the maximum TF magnetic field stems from the desire to stay with "current" Nb_3Sn magnet technology. In addition, current density scaling proposed by J. Schwartz et al.[9] was used to size the magnets.

One of the most troublesome features of previous DT tokamaks is the need to frequently change out the first wall components due to radiation damage. This not only reduces the reliability and availability of the power plant, but also results in large volumes of radioactive material which must be handled and in increased radiation exposure to plant maintenance personnel. If a permanent first wall, i.e. one that would last for 30 full power years (30 FPY), can be designed, most of these objections can be avoided. The use of low activation ferritic steels dictates that the neutron exposure be limited to < 10 MWy/m^2. In order to provide some safety margin, we have limited the average neutron flux to < 0.1 MW/m^2 or 3 MWy/m^2 for the entire life of the reactor.

One of the most challenging technological features of any tokamak is its ability to withstand the mechanical and thermal effects of a plasma disruption. This is especially true in the case of a D-He3 reactor where the current may be 2-4 times that in a DT tokamak. On the other hand, since D-He3 reactors do not need to breed tritium, there is no need to minimize the metallic structure. This allows one to design very stiff and robust first wall and shield structures that can withstand the mechanical forces associated with 50 MA disruptions. It was determined that the plasma currents should be kept to less than 50 MA for safety reasons.

Apollo operates in the first stability regime, where achievable β values appear to be low in comparison to the modest values of second stability tokamaks. Therefore, the plasma power density is relatively low, and a high energy confinement time is required to limit transport energy loss without unduly increasing the device size. To avoid choking the plasma with fusion ash, the particle confinement time for the ash must then be low compared to present experimental values for the bulk plasma. In order to achieve the Apollo reference value of $\tau_p^{ash} / \tau_E^{bulk} = 1$, active ash pumping will be required. Several methods for enhancing fusion ash transport have been suggested; these invoke instabilities, such as sawteeth, or the use of ion cyclotron range of frequencies (ICRF) waves. The latter methods include using the Doppler-shifted ICRF resonance, ICRF resonance effects on banana orbits, ponderomotive force-induced $\mathbf{F}\times\mathbf{B}$ diffusion, and ponderomotive force effects on orbits. Although none of these have been experimentally verified and preliminary estimates indicate that some methods may require larger powers, the ash-pumping problem has so far received only a small amount of study. The swiftly developing state of knowledge in the fields of ICRF-plasma interactions and stochasticity theory give some confidence that the problem can be resolved favorably.

Another goal of the fusion program has been to avoid the necessity of deep underground storage of radioactive waste from fusion power plants. Some success has been made by postulating chemical changes in structural alloys to achieve the Class C, low level waste classification for steels and vanadium alloys. Even with Class C wastes there are some restrictions on the form of the containment; the depth of disposal must be >5 meters, and 500 year monitoring of the facility is required The use of Class A waste (obviously less radioactive than Class C waste) removes some of the restrictions as to depth (>1 meter), the time over which waste must be monitored (100 years), and the form of waste container. If Class A can be achieved, it should help in the public acceptance of fusion energy.

The ability of a fusion reactor to avoid high radiation exposures at the site boundary during an accident can have both an economic as well as safety advantage. There are at least 4 levels of safety which have been defined for fusion nuclear plants[10,11] with the term "Inherently Safe" given to the most desirable case. This level of safety limits the exposure of civilians at the site boundary to less than 200 rem during the accident. Therefore, the goal of the Apollo series of reactors has been to achieve a Level 1 safety rating. This will also allow the components outside the nuclear island to be non-nuclear grade and thereby result in a lower cost of electricity.

APOLLO-L3 GENERAL DESCRIPTION

Key parameters for the Apollo-L3 reactor are given in Table 2 along with the most current values for ARIES-I.[7] The plasma geometry of Apollo-L3 is compared to ARIES-I and ITER[12] in Figure 1a and 1b, respectively, where it can be seen that, in spite of the lower power density characteristic of the D-He3 reaction, the lower magnetic field on the Apollo TF coils, and a more

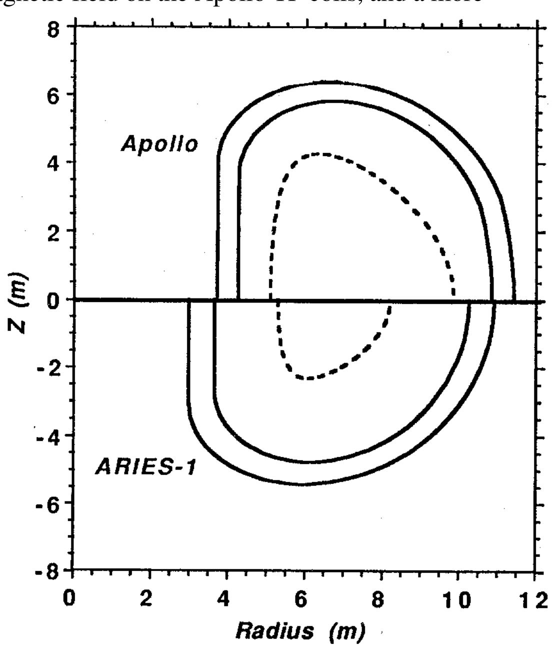

Figure 1a. Comparison of plasma shape and volume in Apollo-L3 with that in ARIES -1.[7]

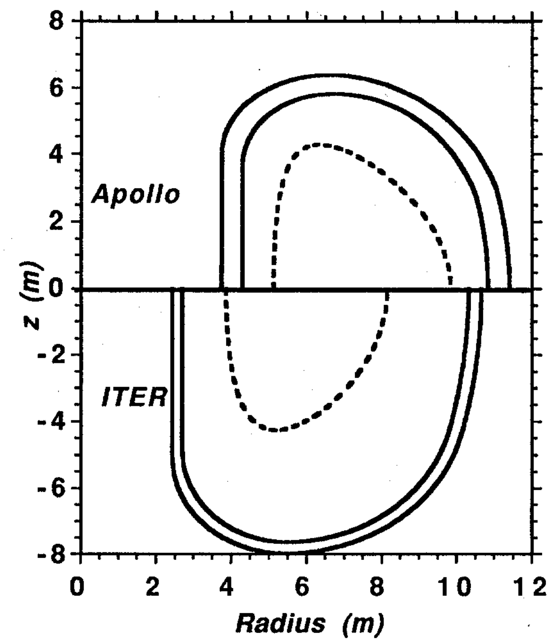

Figure 1b. Comparison of plasma shape and volume in Apollo-L3 with that in ITER.[12]

Table 2. Key parameters of Apollo-L3.

Parameter	Apollo-L3	ARIES-I[7]
Aspect Ratio	3.15	4.5
Major Radius (m)	7.47	6.75
Max. Field @ TF Coil (T)	19.3	21.3
Field @ Plasma Center (T)	10.9	11.3
Electron Density (10^{14} cm^{-3})	1.92	1.45
Ion Temp. (keV)	58	20
Beta (%)	6.7	1.9
Troyon Coefficient	0.035	0.032
Plasma Current (MA)	49	10
$q(\psi)$	2.67	4.5
Energy Conf. Time(s)	13	2.5
ITER-p H-mode Coefficient	3.5	2.6
$n_e\tau_E$ (10^{14} s/cm^3)	25	3.7
Avg. n Wall Load (MW/m^2)	0.1	2.5
Avg. FW Heat Flux (W/cm^2)	87	38
Fusion Power (MW)	1923	1926
Synchrotron Power (MW)	940	196
Bremsstrahlung (MW)	518	45
Transport Power (MW)	435	245
D-D Neutron Power (MW)	29	1
D-T Neutron Power (MW)	96	1539
Inj. Current Drive Power (MW$_e$)	96(NBI)	97(RF)
Direct Conv. Eff. (%)	80	0
Thermal Conv. Eff. (%)	44	49
Net Electric Power (MW$_e$)	1000	1000
Net Efficiency (%)	47	39

conservative thermal power cycle, the overall reactor volume of Apollo-L3 (inside the TF coils) is not that much greater than a DT reactor.

As would be expected, the ion temperature is ≈3 times higher in the D-He3 plasma. The temperature at the center of the plasma is about a factor of 2 greater than that achieved in TFTR.[13] The lower aspect ratio gives a much higher beta value in Apollo.

One of the main differences in the first stability D-He3 tokamak reactor compared to ARIES-I is the plasma current (49 vs. 10 MA). Some perspective on this difference is shown in Figure 2 where the historical data on plasma currents in existing and projected devices are plotted. The highest current achieved thus far is 7 MA in JET[14] and the next large device to be built, CIT,[15] will extend this to 12 MA. The plasma current in ITER[12] will be 22 to 28 MA and a recent proposal by Rebut[16] would require a 30 MA plasma in JIT. The plasma current required in Apollo-L3 is roughly a factor of 2 larger than that in ITER or JIT.

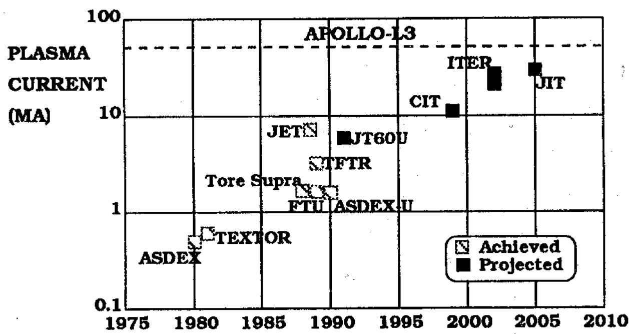

Figure 2. Historical and future development of plasma current in fusion devices.

The $n_e\tau_E$ value required for Apollo is ≈6-7 times that for a DT reactor like ARIES-I, most of which comes from the longer confinement time required, not the plasma density.

One of the most critical technology parameters for a reactor, the neutron wall loading, is 25 times lower in Apollo-L3 than in ARIES-I. This is the basis for achieving at least 3 of our major goals; the permanent first wall, Class A waste with "conventional" construction materials, and Inherently Safe operation.

The average first wall heat flux is only 2 times that in ARIES-I, even though essentially all of the fusion energy in Apollo-L3 is emitted as charged particles or photons, compared to 20% in a DT reactor. The larger plasma chamber and the direct conversion of some of the synchrotron energy is responsible for bringing the D-He3 and DT heat flux numbers closer together.

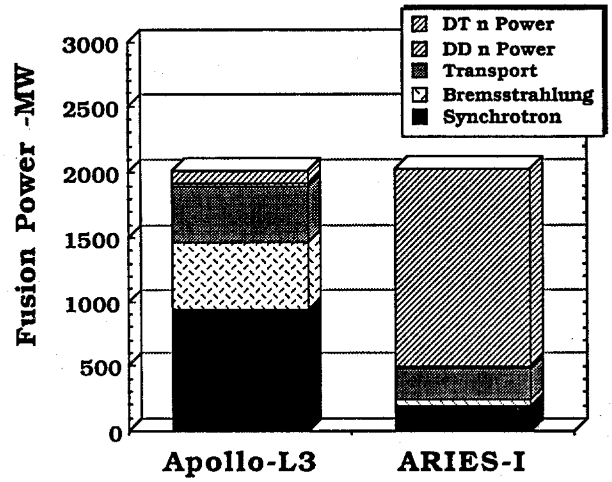

Figure 3. Comparison of energy release mechanisms from the plasma in a typical D-He3 (Apollo-L3) and a DT (ARIES-I) power plant.

It is of interest to note that the total fusion power is roughly the same for both D-He3 and DT even though the components that make up that energy release are quite different. Apollo-L3 releases almost 50% of its power in synchrotron radiation (see Figure 3) and roughly one quarter each in bremsstrahlung and particle transport energy. This is to be contrasted to ≈ 80% in neutrons and ≈10% in photons and another 10% in particle transport in ARIES-I.

The energy released in Apollo-L3 is converted to electricity in two different ways. First, over 60% of the synchrotron radiation is converted directly to electricity via rectennas[17] at an efficiency of 80%. The rest of the energy is converted to electricity via a thermal Rankine cycle utilizing an organic coolant.[18] The efficiency of the organic cycle is 44%, consistent with the analysis of Lewis.[19] This is lower than the 49% efficiency calculated for the He cooled SiC in ARIES-I. However, such a high efficiency is only achieved by running the SiC at 1000°C while it is subjected to high neutron fluxes. The lower efficiency in Apollo-L3 is balanced by the lower cost use of “conventional” steel alloys running at ≈550°C at very low irradiation levels. Furthermore, the use of lower technology materials, at lower temperatures, and lower radiation levels should translate into higher reliabilities and fewer nuclear grade components. The overall net efficiency for Apollo-L3 is 47% vs. 39% for the SiC structure/ARIES-I design because of the direct conversion of synchrotron radiation. If the same high technology energy conversion scheme (SiC/He) were used in Apollo-L3, the overall net efficiency would be >50%.

PHYSICS ANALYSIS OF APOLLO-L3

The main physics parameters of Apollo are shown in Table 2. The plasma is vertically elongated with triangularity. Beta is determined by the Troyon formula with a coefficient of .035. The main losses from the plasma are synchrotron radiation, bremsstrahlung, and plasma transport, in that order. Synchrotron losses are calculated using the Trubnikov formula[20] with appropriate averaging of the density and temperature profiles. The synchrotron loss has been checked using the CYTRAN code;[21] the results agree within 3%.

The energy confinement time of 13 s can be obtained from ITER 1989 power law scaling[22] with an L-mode multiplier of 3.5. This is slightly larger than that given by the present experimental database (≈3).

The plasma current is 49 MA. The bootstrap current accounts for 17 MA, synchrotron current drive provides 23 MA, and neutral beam injection drives the remaining 9 MA, (see Figure 4). The synchrotron radiation is transported to the microwave conversion system outside the reactor using waveguides. Synchrotron current drive is accomplished by angling the waveguides to remove net angular momentum from the radiation field; the reaction back on the electrons drives the plasma current. Because of the electrical resistivity of beryllium, about 35% of the synchrotron radiation is absorbed in the first wall and not transported down the waveguides. At present, the bootstrap current is well accepted, but the demonstration of synchrotron current drive awaits the creation of plasmas with sufficient synchrotron power generation. However, the basic physics of synchrotron current drive is the same as that of electron cyclotron current drive, which has been demonstrated, giving some confidence in this assumption.

In the power and particle balance analysis, it has been assumed that the particle confinement time equals the energy confinement time. This results in a thermal ash

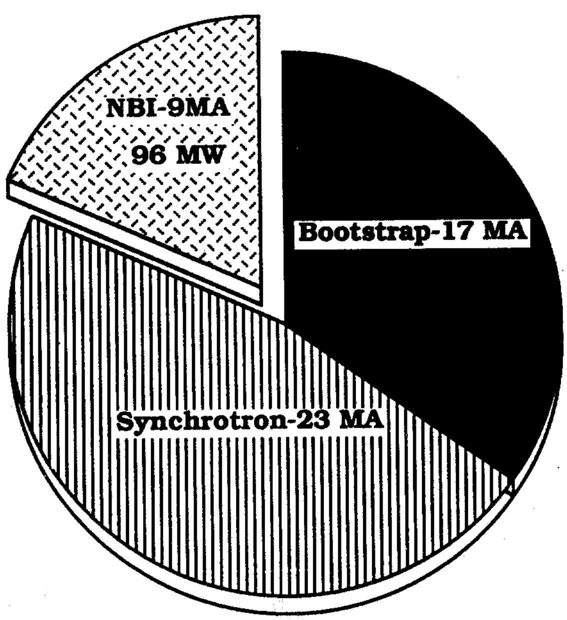

Figure 4. Current drive mechanisms in Apollo-L3.

concentration of 4.2% protons and 4.0% alpha particles. Increasing τ_p^{ash}/τ_E substantially above 1-1.5 quickly leads to choking the plasma with ash at a given τ_E, and thus requires reducing τ_E, resulting in increased transport losses and difficulty in maintaining plasma power balance. The net effect is that COE is a steeply rising function of τ_p^{ash} / τ_E. In the second stability regime, where synchrotron radiation losses are usually lower than in the first stability regime, the τ_p^{ash}/τ_E upper limit is 2-3. This compares with a value of τ_p/τ_E of 4 for the ARIES-I DT reactor design. Consequently, ash removal is a more significant problem in D-He3. The present database for plasma transport suggests that under normal operation, an active means of removing ash from the plasma may need to be developed.

TECHNOLOGY CONSIDERATIONS

There are 5 key technology design areas in the Apollo-L3 reactor:

- High Field TF Coils
- Heat Flux on the First Walls
- Shield Design
- Disruption Effects
- Low Radiation Damage
- Synchrotron Energy Direct Conversion[17]

HIGH FIELD TF COILS

There are two major concerns here:

- Can one make reactor size 19 tesla TF coils?
- How much stored energy is there in the TF coils?

The first question was addressed by scientists at MIT,[23] in Apollo-L3, and more recently in the ARIES project.[7] The conclusion of both studies is that the choice of a 20 T coil for Apollo-L and a 21.3 T coil for ARIES-I is not unduly optimistic. In 1987, scientists at MIT fabricated Ti modified Nb_3Sn wire capable of carrying 20,000 A/cm^2 at 20 T @ 4.2°K.[23]

The stored energy in the TF coils for both a D-He3 and a DT fusion power plant has been calculated. While the TF coils for Apollo-L3 can be made at lower magnetic fields, they do contain slightly more stored energy because of their larger size.

HIGH HEAT FLUX CONSIDERATIONS

The large reduction in neutrons in Apollo-L3 suggests that there might be a much higher heat flux to the first wall. This is partially mitigated by the lower power density in the plasma which results in a larger first wall area. Furthermore, the direct conversion of synchrotron radiation to electricity also reduces the amount of heat absorbed in the first wall. Figure 5 compares the 87 W/cm^2 average heat flux to other fusion reactor designs and it reveals that the FW heat flux in Apollo-L3 is lower than TITAN[24] and STARFIRE,[25] while being 1.5 to 2 times the ITER[12] and ARIES-I designs, respectively. Also plotted in Figure 5 is the average heat flux to the divertor in the same devices. One notices that the divertor heat flux in Apollo-L3 is generally the same as other conventional DT toroidal devices.

SHIELD DESIGN

The main function of the shield is to protect the superconducting magnets from radiation damage. There is ≈300 MW of neutron energy deposited in the shield and it was decided to recover this heat in a high temperature organic coolant cycle. The physical layout of the inboard and outboard shields is given in Figure 6. The structural material is low activation ferritic steel[26] and the organic coolant is OS84, a reactor grade terphenyl. The thickness of the shields is determined by the neutron fluence limit for the Nb_3Sn superconductor (10^{19} n/cm^2 over 30 FPY's). The optimized shields are made up of 70% steel and 30% organic coolant. The inboard shield thickness is 65 cm (88 cm from the edge of the plasma to the winding pack). The outboard shield thickness is 80 cm (110 cm from the plasma edge to the winding pack).

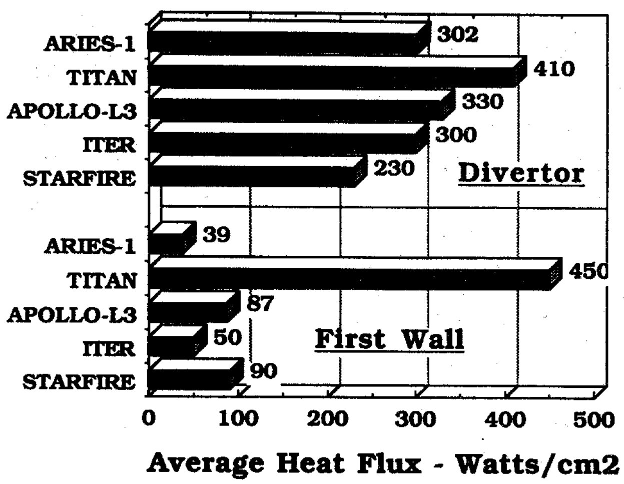

Figure 5. Heat fluxes in D-He3 reactors are comparable to DT fusion devices.

The inlet coolant temperature to the shield is 340°C and the outlet temperature is 425°C. This means that the temperature of the ferritic steel ranges from 340°C in the back of the blanket to 550°C on the plasma side of the first wall.

The divertor design is an organic cooled, Be coated steel structure which runs at a maximum temperature of 600°C in a relatively low neutron flux region (≈0.06 MW/m^2).

DISRUPTION EFFECTS

Because of the high plasma currents and temperatures in first stability D-He3 reactors, disruptions are a major concern. The high currents can cause large eddy currents in the surrounding structure, leading to large forces. Similarly, the large amounts of thermal energy in the plasma can cause significant erosion of the first wall and divertor during a quench. Hence, prudent design is needed to ensure a reasonable lifetime.

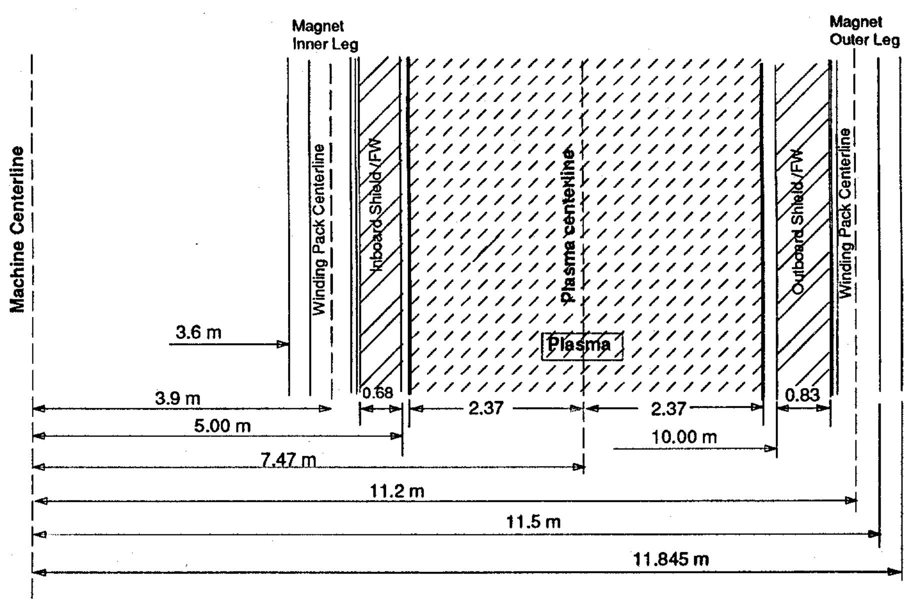

Figure 6. Schematic of Apollo-L3 first wall and shield at the midplane.

The electromagnetic effects associated with disruptions may not be as severe as the high plasma currents would suggest. The magnitudes of the eddy currents induced in the first wall and shield are determined by the rate of change of the plasma current. Because the current quench is dominated by the plasma temperature after the thermal quench, the time scale is expected to be similar for DT and D-He3 plasmas. Assuming the same dI/dt for the ARIES-III D-He3 tokamak reactor, which has an even higher plasma current than Apollo-L3, as for ITER, leads to forces on the first wall and coating of $\lesssim$130 kPa [ARIES project meeting presentation, David Ehst, 1990]. These would be smaller than the forces expected in ITER for reasons outlined below.

A major advantage of D-He3 reactors is that they can be built to withstand high forces because there is much less neutron heating in the structure and there are no breeding requirements. This allow much more robust first walls to be designed. Other than the first wall (which must take the surface heat loads) the D-He3 structure can be built with much thicker sections, leading to significantly higher allowable forces.

Although it appears that the electromagnetic effects of disruptions are tolerable in D-He3 systems, the thermal effects are still severe. As the thermal energy in the plasma is dumped on the first wall, it will likely remove significant amounts of material from the first wall and divertor. Estimates for a first stability version of ARIES-III indicate that removal rates will be on the order of several hundred μm of Be per disruption, depending on the disruption time and the energy density [ARIES project meeting presentation, David Ehst, 1990]. This indicates that reflective coatings applied to the plasma-facing components, such as Be, will have to be replenished *in situ* after a few disruptions, and that the first wall must be made as thick as possible.

While the analysis of disruption effects in Apollo is ongoing, preliminary indications are that the electro-magnetic effects are tolerable, comparable to those in the ITER[22] design The thicker wall in Apollo allows the stresses to be even lower than in ITER. The thermal effects are a problem and must be accounted for in the design.

RADIATION EFFECTS

One of the major driving forces behind the use of the D-He3 cycle is to allow a permanent first wall to be designed. Since there is no high fluence, high energy neutron data for *any* candidate first wall material, we have taken a relatively conservative approach to the lifetime determination. Ferritic steels have demonstrated that they are relatively resistant to neutron damage at high temperature and it is felt that this alloy will be able to achieve at least a 10 MWy/m^2 lifetime in the 500-600°C temperature range.[27] The average neutron wall loading in Apollo-L3 is 0.1 MW/m^2 and the peak value on the outboard side is 0.17 MW/m^2. Over a 30 FPY life, this would amount to an exposure of ≈ 5 MWy/m^2. To insure that we can count on the full life of the wall, we have used an additional factor of 2 for safety. A comparison of the first wall operating conditions in Apollo-L3 to other recent DT reactor designs is given in Figure 7. It is obvious that first wall replacement will be required for the DT reactors.

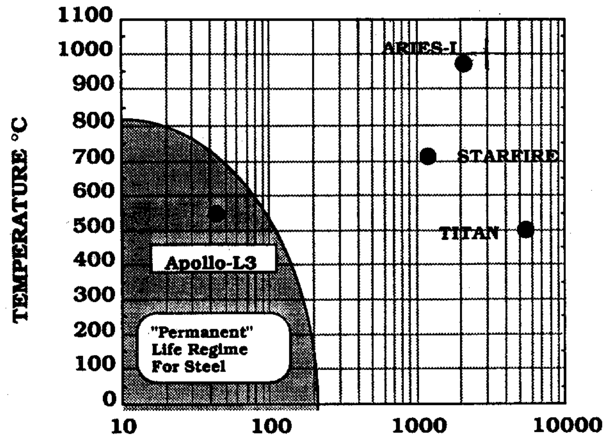

Figure 7. Permanent first walls are only possible for D-He3 reactors.

SAFETY AND ENVIRONMENT

There are three key indicators of the impact that a fusion device could have on the public:

- Inventory of radioisotopes in the reactor during operation.
- Amount of afterheat available and temperature reached in the event of an accident.
- Inventory of long lived radioisotopes after the reactor is decommissioned.

The low neutron level in a D-He3 reactor has a very positive effect on all of the above conditions.

One of the most troublesome radioisotopes to handle is tritium in a gaseous form . There is no way to avoid this problem within DT systems and the vulnerable inventory may range from as much as 700 grams in solid breeder systems such as ARIES-I,[7] to several 1000 grams in liquid metal designs.[28] Release of 2500 g of T_2 (as HTO) can cause exposure levels of 25 rem at the plant boundary,[29] forcing evacuation of civilians.

There is a small amount of T_2 produced in D-He3 reactors by the side DD reactions. In Apollo-L3 approximately 14 grams is exhausted by the plasma per full power day of operation. This T_2 ends up in the exhaust gases and is removed through the vacuum pumps. The mean residency time in the vacuum pumps and separation units is usually on the order of a few hours so that only a few grams of T_2 resides in the reactor tritium processing system during operation. The tritium inventory in the Apollo-L3 design is given in Table 3.

Table 3. Key tritium parameters for Apollo-L3.

Production Rate	Tritium, g
Born in the plasma	31.9 g/d
Burned in the plasma	18.3 g/d
Exhaust from the plasma chamber	13.6 g/d
End of Life Inventory	
First wall	0.8
Divertor plates	7.7
Shield coolant - organic	0.02
Divertor coolant - organic	0.2
Plasma exhaust and reprocessing	2.4
Total	11.12

The active inventory of tritium in Apollo-L3 is ≈11 g. The maximum exposure if ALL the T_2 were released under the worst weather conditions would be less than ~0.1 rem, well below the NRC guideline requiring an emergency site evacuation plan.

In order to calculate the potential hazard due to the release of irradiated structural material, one must know the initiating mechanism. In a fusion reactor, this is usually the afterheat in the blanket/shield or the combustion of the coolant (if flammable). The level of afterheat has been calculated and is shown in Figure 8.

Using the shield design previously described for Apollo-L3 and using the computer code ANSYS,[30] the temperature rise in the first wall was calculated for a loss of coolant accident under adiabatic conditions. Calculations show that the temperature drops right after the initiation of the accident, eventually reaching a minimum temperature of ≈300°C. It then continues to rise and reaches 500°C after one week. Such temperatures are not high enough to cause any radioisotopes from the steel to escape and therefore should not contribute to any offsite exposure to the public. One might also ask the question, "What happens if the coolant does not leave the blanket? Could it reach the ignition point?" Because of the heat capacity and thermal conductivity of the coolant, the temperature would not even reach 500°C.

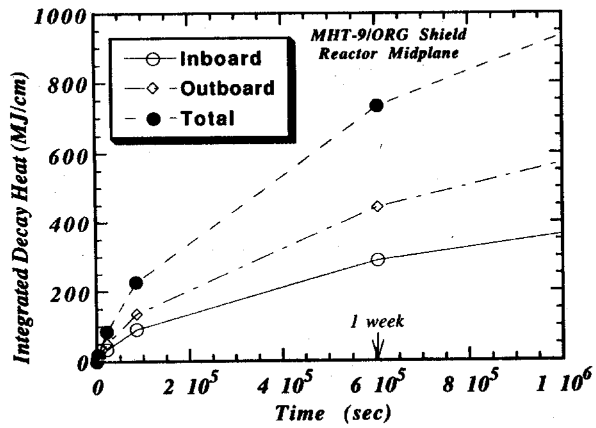

Figure 8. Afterheat in the Apollo-L3 shield after full lifetime exposure. Note this is the amount generated and energy remaining in structure depends on energy loss mechanisms.

The temperature at which the organic coolant would ignite spontaneously in air (20% oxygen) is 420°C. In order to increase the safety margin, it would be prudent to use an atmosphere in the reactor building which consists of only 10% O_2, a sufficient level not lethal to workers but enough to retard any possible combustion of the organic coolant.

The concentration of the long lived radioisotopes in the ferritic steel have been calculated and compared to the levels allowed for class A and class C low level radwaste in the U.S. With the Be coating to reflect the synchrotron radiation on the first wall, the Apollo-L3 FW and shield have a Waste Disposal Rating (WDR) for class A of 0.88. This means that after 30 FPY of operation, the FW and shield (after appropriate time for decay of short lived isotopes) can be removed from the reactor and buried in shallow, low level waste disposal sites. Figure 9 gives the WDR for class A and class C low level waste. The Co-60 isotope is the major contributor to the class A WDR, and Nb-94 dominates the class C WDR.

One of the main benefits of the low inventory of volatile radioisotopes and small stored energy in afterheat is the ability to achieve the Level 1 - Inherently Safe condition for Apollo-L3. The practical significance of this rating is that many of the components do not have to be Nuclear Grade (NG) and thereby will lower the cost of Apollo-L3. This will become more apparent in the economics section.

ECONOMIC CONSIDERATIONS

Costing analyses of fusion power plants have progressed significantly in the past several years.

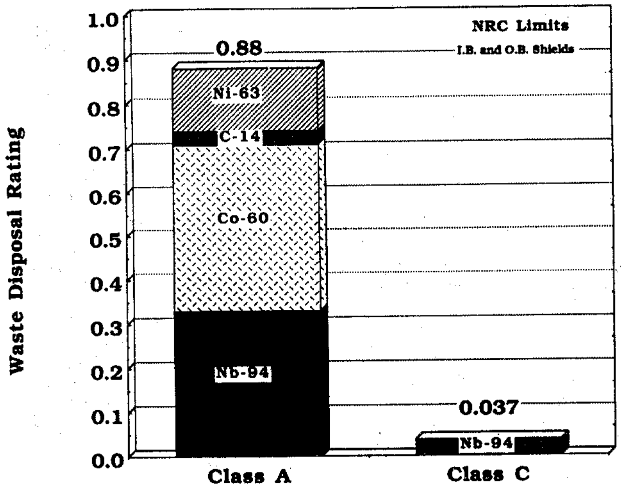

Figure 9. The low activation ferritic alloys qualify as low level class A wastes. The waste disposal rating for class C is 0.037 which is more than a factor of 25 below the class C limit.

Standardized codes, some of them originating from the CIT[15] and ITER[12] efforts have been updated and made more flexible. In the tokamak area, the Generomak[31] code has allowed rapid assessments of cost trends and the Systems Code[32] developed by the members of the ARIES team has allowed optimization of both physics and technologies. We have used both codes, as well as internally developed codes for the cost optimization. The details of the economic assumptions can be found in references[31-33] and we will concentrate only on the results for this paper. Slight differences exist in plasma physics assumptions between the UW tokamak physics code, RAGE, and the ARIES system code. The ARIES code was modified to give the same radiation and transport powers as the UW code, and the quoted cost numbers were then generated using the ARIES code. A correction to the ARIES code output was also applied to reduce an unnecessary 1.8 m gap between the outboard shield and the magnet.

Table 4 lists the key economic parameters for Apollo-L3 in constant 1990 dollars utilizing the ARIES cost code.[33] These are compared to the latest ARIES-I numbers to illustrate the main differences between the most advanced D-He3 and DT fusion reactor designs. The direct capital cost for Apollo-L3 is ≈2050$/kWe. This cost includes the credits for Level 1 safety assurance as opposed to the LSA-4 for which the cost codes are normalized. Such a direct cost is ≈10%, lower than a LSA-4 design.

Finally, the cost of He3 fuel at 1000 $/g contributes ≈11 mills/kWh to the COE, approximately the same as replacement of damaged first wall components in a

Table 4. Key economic parameters for Apollo-L3.

	Millions of Dollars (1990)	
Costs for a 1000 MWe Power Plant	D-He3 Apollo-L3	DT ARIES-I
Safety Level	LSA=1	LSA=2
Land	10	10
Structures and Site Facilities	285	291
First Wall/Blanket	5	490
Shield	94	204
Magnets	471	339
Structure	102	55
Supplemental Heating/CD	282	108
Other Reactor Equipment	193	215
Total Reactor	1442	1712
Heat Transport and Transfer	42	186
Rectennas and Turbine Plant	416	233
Electric Plant Equipment	101	71
Misc. Plant Equipment	46	52
Direct Cost	2047	2254
Indirect Cost	853	939
Contingency	423	539
Total Cost (and $/kWe)	3323	3732
Interest During Construction	548	618
Total Cost (and $/kW$_e$)	3871	4350
Levelized Power Cost (mills/kWh)		
Availability	80	76
Capital Investment	53.4	63.2
Operations & Maintenance	4.3	5.5
FW/Bl/Divertor Replacement	0.02	10.9
Fuel	11.3	0.03
Decommissioning	0.25	0.5
Cost of Electricity	69.2	80.2

DT reactor like ARIES-I. However, the low neutron exposures that result from the use of this fuel have at least three economic benefits with respect to the COE. First, the permanent first wall in a D-He3 system should increase the plant availability, i.e., if the DT systems (ARIES-I) can achieve 76% plant availability while changing the first wall and blanket every 2-4 years, then the Apollo-L3 reactor should be able to reach availabilities of 80% with a permanent wall. Second, the cost of replacing the damaged components in DT systems with new modules can be rather expensive. In the ARIES-I design, approximately 14% of the COE (≈11 mills/kWh) is attributed to radiation damaged components. Third, the low inventory of volatile radioisotopes, and the lack of a credible mechanism to release them, allows us to achieve Level 1 (inherent) safety which in turn allows the D-He3 plant to use many non-nuclear grade components with a cost savings of ≈18% (>16 mills/kWh). Other unquantifiable benefits of the low radiation levels should be an increased public acceptance and a shorter licensing time. The shorter licensing time would reduce the interest during construction and possibly the indirect costs.

CONCLUDING REMARKS

The preliminary design of another in the Apollo series of D-He3 tokamak reactors again shows the compelling advantages associated with this fuel cycle:

- Permanent first wall
- Class A wastes
- Level 1 (inherent) safety ranking
- Highly competitive COE compared to DT systems.

However, the challenges are great:

- High plasma currents
- Higher $n\tau_E T$ requirements
- Direct conversion of synchrotron radiation
- Ash removal.

It is also worth noting that the tokamak is not the optimal configuration for burning the advanced fuel He3. Other, higher beta, more open systems would seem to be very attractive. It would be very helpful if future work could concentrate on the alternate confinement concepts. In any case, it is clear that the D-He3 fuel cycle does represent a higher potential for fusion energy in the 21st century and must be included in long range energy planning.

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