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ABSTRACT

A preconceptual design of a tokamak reactor fueled by a D-He-3 plasma is presented. A low aspect ratio (A=2-4) device is studied here but high aspect ratio devices (A > 6) may also be quite attractive. The Apollo D-He-3 tokamak capitalizes on recent advances in high field magnets (20 T) and utilizes rectennas to convert the synchrotron radiation directly to electricity. The overall efficiency ranges from 37 to 52% depending on whether the bremsstrahlung energy is utilized. The low neutron wall loading (0.1 MW/m^2) allows a permanent first wall to be designed and the low nuclear decay heat enables the reactor to be classed as inherently safe. The cost of electricity from Apollo is > 40% lower than electricity from a similar sized DT reactor.

INTRODUCTION

One of the greatest worldwide challenges in the 21st century will be to provide a safe and secure energy supply which can help to feed, clothe, warm, cool and protect the Earth's anticipated 10 billion inhabitants. The enormity of this task is illustrated by a simple calculation. To provide the energy needed by this future population just at today's average energy consumption rate of 10 barrels of oil equivalent (BOE) per capita per year will require 10 trillion BOE (10 billion people x 10 BOE/y-person x 100 years) during the 21st century. This is at least twice the energy remaining in economically recoverable coal, oil and gas and it is 2-3 times more than the energy contained in the world's reserves of uranium used in once-through LWR fuel cycles. This calculation does not address the drive to increase the standard of living for the developing nations of the world or the environmental impact of burning such an immense amount of fossil fuels (e.g., the greenhouse effect, acid rain, solid wastes, etc.) or the large amount of radioactive waste which will be generated from the use of 30 million metric tonnes of uranium.

If there is to be a viable 21st century (let alone a 22nd century) it is clear that other forms of energy must be developed. Renewable energy forms (solar, wind, etc.) can help in selected locations but the only form of energy presently known that can fill this tremendous need for centuries to come is nuclear energy in the form of fission breeders or fusion.

Today, the worldwide fusion program (not quite 40 years old) is concentrating on the DT fuel cycle for obvious physics reasons; it is the easiest reaction to achieve in the laboratory. Tremendous progress has been made in this field as illustrated by the fact that the product of the three most critical parameters of a fusion device, the plasma temperature T, the plasma density n, and the plasma confinement time τ, has increased by a factor of 20,000 over the past 20 years.[1] This product is now within a factor of 2 of the conditions needed to reach breakeven in DT reactors, a fact which should be accomplished in either TFTR[2] or JET[3] by 1991-92. However, there are two significant disadvantages with the DT fuel cycle stemming mainly from the facts that (1) 80% of the energy of this reaction is released in the form of neutrons and (2) there is a need to breed, control, and contain large amounts of radioactive T_2.

The 14.1 MeV neutrons cause severe damage to high temperature structural components making their useful life much less than the 40 years one hopes to run a power plant. In addition, the neutrons cause a significant amount of radioactivity in the surrounding structure which must be adequately contained in the event of an accident in order to protect the public. The tritium inventory in a 1000 MWe DT power plant will be in the 10-100 million curie level and, given the difficulty of containing such an elusive gas, considerable safety features will be necessary.

Scientists and engineers have now begun to think beyond the first generation of fusion fuels (DT) that will provide the physics base for much safer and potentially more economic second generation fusion fuels. One advanced fuel cycle which has been examined at various times over the past 25 years is that of D and He-3. This reaction,

$$D + He\text{-}3 \rightarrow p\ (14.7\ MeV) + He\text{-}4\ (3.7\ MeV)$$

optimizes at a temperature of roughly 3 times that of DT (60 keV vs. 20 keV) and requires Lawson $n\tau_E$ values of 3-4 times that of the DT cycle. In other words, the required $n\tau T$ product is ~ 10 times that required of DT, but considering the fact that scientists have increased that product by a factor of 20,000 over the past 20 years, it is entirely conceivable that the more challenging physics conditions can be achieved in magnetic devices (such as CIT[4] and NET[5]) now envisioned to operate in the 1990's. By the year 2000 it is possible that not only breakeven, but also ignition of this fuel could be demonstrated. Recent experiments at JET[6] in the U.K. have produced over 60 kW of thermonuclear power with the D-He-3 cycle and levels of 100 kW or more are anticipated within a year. This is significantly more power than has been generated with the DD cycle as of early 1988 (11.4 kW) and the DT cycle has not yet been tested. No surprises in the physics have been discovered thus far and none are expected as experiments progress into the MW level. Anticipating such an exciting possibility, one can now ask the questions, "What would a reactor based on this cycle look like and what would the environmental and economic advantages of such a system be?"

The objective of this paper is to examine the above question with respect to a tokamak. Miley has examined the reactor implications of D-He-3 for some magnetic configurations in the past[7] and recent papers by Wisconsin scientists have examined this question as it pertains to a linear tandem mirror reactor.[8,9] The problem of obtaining an adequate helium-3 fuel supply, which used to be the main reason for neglecting this fuel cycle, has been solved by the recent discovery of lunar sources amounting to a million metric tonnes.[10-12]

TOKAMAK DESIGN PHILOSOPHY

It is obvious that the design of a commercial D-He-3 tokamak requires extrapolation of present day physics both in temperature ($\langle T_i \rangle \cong$ 60 keV is needed for reactor operation compared to the maximum peak temperature of ~ 30 keV already experimentally achieved)[13] and in $n\tau$ (60×10^{14} vs 2×10^{14} presently achieved).[12] Emmert et al.[14] have demonstrated that such plasma conditions could be achieved in upgraded DT devices, such as NET,[5] but those devices are primarily designed for DT operation and therefore are encumbered with bulky shielding and complicated T_2 breeding blankets. High field devices, such as Ignitor[15] or Candor,[16] are more suited to a D-He-3 cycle as would be FRC's[17] but the scope of this paper is purposely confined to the "conventional" tokamak in order to investigate the maximum advantages that could be achieved with the world's current leading confinement concept. Later papers will address the higher beta systems.

Once the tokamak was chosen for this study, another decision had to be made with respect to the operating beta regime. One choice would be to operate in the first stability regime which, in turn, strongly favors a low aspect ratio (2-4) device. A second choice would be to operate in the 2nd stability regime which would favor a high aspect ratio (> 6) configuration. The advantages and disadvantages of these two choices are outlined in Table 1. The low beta system builds on a large body of worldwide physics information but results in very high plasma currents which could be a problem in the event of a disruption and if bootstrap or synchrotron current drive is not available. The high beta tokamak has the advantage of

Table 1. Key Features of Low and High Aspect Ratio Tokamaks

Plasma Configuration	Main Advantages	Main Disadvantages
Low Beta (1st Stability) Low to Moderate Aspect Ratio (2-4)	• Builds on current world program	• High plasma current
	• High synchrotron fraction	• High magnetic field
High Beta (2nd Stability) High Aspect Ratio (> 6)	• Low magnetic field	• Unconfirmed physics
	• Low plasma current	• Larger device
		• Low synchrotron fraction

relatively low magnetic fields (~ 10 T vs 20 T) and relatively low currents (~ 10 MA vs 50 MA) but the physics base is almost nonexistent. If the 2nd stability physics can be demonstrated it would clearly be an attractive choice. However, it was felt that the conservative approach at this time would be to investigate the low beta, low-aspect-ratio design (hereafter referred to as Apollo-L) and subsequent high aspect ratio Apollo designs will be aimed at the higher beta configurations (Apollo-H).

The next step in the Apollo-L design was to perform a parametric physics analysis based on a 1200 MWe net power output. This power level was chosen so as to compare to the previous ESECOM[18] study of the environmental aspects of DT fusion power. The physics assumptions used in this analysis will be described later in this paper but the main constraints are listed below.

- **Net Power = 1200 MWe**
- **TF Maximum Magnetic Field < 24T**
- **First Wall Neutron Loading < 0.1 MW/m^2**

As evidenced above, one of the key technology parameters is the allowable magnetic field in the toroidal field (TF) superconductors. Today, maximum field values of 16 T are achievable with Nb_3Sn and the Japanese[19] are planning a LCT sized TF coil with this technology. Recent progress in powder metallurgy has produced 20 T filaments with current densities of 10,000 A/cm^2 and it is anticipated that even 24 T coils could be available by the turn of the century.[20] Therefore, Apollo-L designs were examined at 15, 20, and 24 T and the coil scaling laws (i.e., J vs. B) of the Generomak[21] code were used.

The limit on the average neutron wall loading of less than 0.1 MW/m^2 was invoked in order to be able to use structural components for the full reactor lifetime of 30 full power years (FPY) (~ i.e. 3 MW-y/m^2 or ~ 40 dpa). We also wish to demonstrate that components from a decommissioned Apollo-L reactor could be classified as low level waste and that the reactor is inherently safe with respect to loss of coolant accidents (LOCA).

Finally, the issue of energy conversion was addressed. The D-He-3 fuel cycle operates at high temperature and high matnetic field, consequently, synchrotron radiation is an important loss mechanism. Direct conversion to electricity of charged particle energy or photon (synchrotron) energy was also considered. One difficult decision had to be made with respect to bremsstrahlung, transport, and neutron power. The question of whether to convert that energy to electricity through a thermal cycle or to discard it through the cooling tower was decided ultimately on the basis of the cost of electricity. This was addressed using the Generomak[21] costing code, the results of which will be discussed later.

The rest of this paper will summarize the Apollo-L design as it appeared in late 1988. Further optimization will be necessary before the design is finished in 1989.

APOLLO-L GENERAL DESCRIPTION

Key parameters of the Apollo-L reactor and its variants are given in Table 2 and a comparison of the plasma configuration to a previous reactor design is shown in Figure 1. Using a maximum TF coil field of 20 T (see the technology section for a justification of this value), the major radius of the first 1200 MWe reactor studied with full thermal energy conversion is 5.2 meters. In the first case (i.e., 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 52%. 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% (minus the internal energy required by the plant). The direct capital cost (see the economics section) is $1.78 B and direct capital cost per kWe is $1461. The levelized cost of electricity (COE) is ~ 34 mills per kWh at 75% capacity factor (CF).

It can be seen that the plasma current is 69 MA (3-4 times higher than required by a DT power plant) and the average ion temperature is 52 keV, about 2-3 times higher than DT power reactors might require. The $n\tau_E$ product (transport losses only) is 44 x 10^{14} cm^{-3}s which is roughly 10 times the value characteristic of

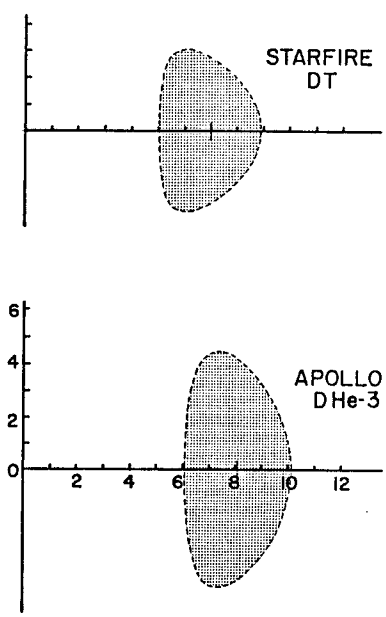

Fig. 1. Comparison of the plasma profiles of two 1200 MWe tokamak fusion power plants, STARFIRE[28] and Apollo.

Table 2. Key Parameters of Apollo-L 1200 MWe Fusion Reactor Design

Parameter	Unit	Microwave & Thermal Conversion (Apollo-LTW)*	Microwave Conversion Only (Apollo-LSW)*	Microwave & Thermal Conversion (Apollo-LTS)*	Microwave Conversion Only (Apollo-LSS)*	Microwave Conversion Only (Apollo-LSS)*
Inboard Shield		W/B_4C	W/B_4C	SS/B_4C	SS/B_4C	SS
Plasma						
B_{max}	T	20-->				
B_{Plasma}	T	9.23	9.52	8.85	9.19	12.9
Plasma Current	MA	69.1	79.5	68.8	80.0	47
Beta	%	12.5-->				6.3
Avg. Ion Density	10^{14} cm^{-3}	1.66	1.37	1.53	1.28	1.27
Avg. Ion Temperature	keV	51.8	67.5	52.0	68.0	69
τ_E	s	27	30	27	32	38
$n\tau_E$	10^{14} s cm^{-3}	44	42	42	41	48
He3/D Density ratio	--	1.09	1.0	1.0	0.91	0.77
Geometry						
Aspect Ratio	--	2.5--->				4
Major Radius	m	5.2	5.8	5.4	6.1	8.0
Horiz. Half Width	m	2.08	2.32	2.16	2.42	2.01
Elongation	--	2.2-->				
Inboard width[a]	m	0.72	0.72	0.85	0.85	0.85
Plasma Volume	m^3	977	1356	1094	1539	1410
Plasma Surface Area	m^2	717	892	773	971	1071
Power						
Fusion Power[b]	MW_t	2347	3160	2259	3155	2872
Net Electric Power	MWe	1218	1175	1180	1196	1204
Net Efficiency	%	52	37	52	38	42
Synch. Power	MW_t	1040	1724	1033	1761	1626
Bremsstrahlung	MW_t	1117	1196	1032	1149	959
Divertor Power	MW_t	201	251	202	253	192
D-D Neutron Power	MW_t	18.5	28.2	19.2	30.5	33.6
D-T Neutron Power	MW_t	53.7	66.3	56.6	72.9	84.6
Avg. n Wall Load	MW/m^2	0.092	0.096	0.089	0.096	0.10
Avg. FW Heat Load[c]	W/cm^2	150	130	129	115	91
Economic[d]						
Direct Capital Costs	B$	1.402	1.250	1.357	1.231	1.444
Total Overnight Capital Cost	B$	2.097	1.869	2.028	1.841	2.159
Direct Capital Cost Density	$/kWe	1151	1064	1150	1029	1199
COE	mills/kWh	34.3	32.4	34.4	31.5	34.6

(a) Inboard distance from plasma to winding pack of TF coils.
(b) Does not include neutron energy multiplication or injected power.
(c) Includes all of bremsstrahlung and 1/3 of particle loss.
(d) For the case of partial nuclear components, He-3 costs=200$/g, Capacity Factory (CF)=75%.

*See Economic Analysis for explanation of designators.

a DT reactor because of high synchrotron losses in Apollo.

From the neutronic side, the roughly equal He/D density ratio and 50% tritium burn up results in a nominal 0.1 MW/m^2 wall loading (about 40 to 50 times lower than a DT power plant) and some 72 MW of neutron power is generated. This value is 40 times lower than in a DT system. The resulting effect on radiation damage, radioactivity and afterheat will be covered in later sections.

Three variations of the first case were considered. First, the effect of maximizing the synchrotron radiation and disposing of the bremsstrahlung, divertor, and neutron power directly to the cooling tower was examined. This resulted in a bigger plasma (R = 5.8 m vs. 5.2 m) and a larger plasma current (80 vs. 69 MA). The total neutron power also increased from 72 to 94 MW and the overall efficiency dropped to 37%. Table 2 also shows that the economic parameters of the two different conversion cycles are roughly equal (assuming equal availabilities although one might argue the solid-state rectenna conversion of microwaves would be more reliable than high temperature-high pressure power cycles with turbines). It was determined that the difficulty in handling the high plasma currents in the event of a disruption needs to be balanced against the potential for higher availability through a simpler balance of plant (BOP).

Next, the effect of using a "low performance" neutron shield (i.e., steel vs. tungsten) was also examined. There was very little effect on the plasma requirements and the COE was slightly lower because the lower shield costs required more than offset the slightly larger machine costs. Further optimization of the power cycle might help this case.

Finally, it was felt that a plasma current of 80 MA may be too difficult to handle, especially during a disruption. Therefore, the aspect ratio was increased to 4 in order to lower the current to 47 MA The base case for the rest of this paper is considered to be the direct conversion of microwaves to electricity in a tokamak with a steel shield.

PHYSICS ANALYSIS OF APOLLO

The analysis of the physics performance is based on beta limits, energy loss mechanisms, and power balance considerations for the plasma. Since the plasma is in the first stability regime, the beta is assumed to be given by the Troyon[22] formula (Troyon coefficient equal to .035); this determines the plasma pressure, which includes the contribution due to fast ions.[23] The most important energy loss channels are synchrotron radiation and bremsstrahlung. At the high magnetic field strengths considered, the plasma current is large and transport across the magnetic field is not as important as the radiation losses. Bremsstrahlung (including relativistic corrections) can be readily calculated since the emission process is classical and reabsorption is weak. Synchrotron radiation, while a classical process, is more uncertain since reabsorption is strong. Our study uses the Trubnikov[24] formula to estimate losses due to synchrotron radiation. Transport of plasma across the magnetic field is treated using scaling laws based on experimental data.[25] The ASDEX H-mode scaling is used with a cutoff given by the neo-Alcator formula. The impurity concentration is taken to be 1% oxygen. The plasma assumptions for beta and confinement scaling are considered to be aggressive by present standards for near term facilities (e.g. NET or ITER) but may be achievable in longer term power reactors.

The parameters defining the performance of Apollo were given in Table 2 for five different design options, each with a net electrical output of about 1200 MWe. When only the synchrotron power is converted to electricity, the major radius and fusion power are larger because of the reduced overall efficiency. A higher ion temperature is used in the microwave conversion case only in order to maximize the fraction of the amount of synchrotron radiation. Shown in Figure 2 is the effect of the toroidal magnetic field at the magnet on the cost of electricity. This figure assumes only microwave conversion and a steel neutron shield. There is a clear benefit in increasing the magnetic field strength to 20 T, but above 24 T the COE rises. This is due to the constraint of a constant neutron wall load which requires a decreased D/He ratio of the fuel at high B.

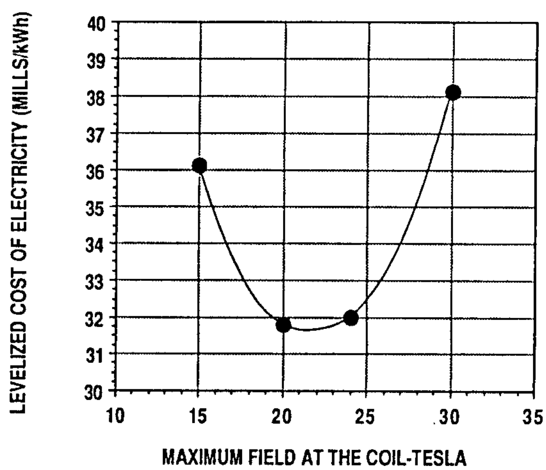

Fig. 2. Effect of toroidal magnetic field on the levelized cost of electricity in the low aspect ratio (A=2.5) partial nuclear grade D-He-3 tokamak, Apollo-L.

The high plasma current in Apollo is a concern because of the problem with plasma disruptions and power required for current drive if no bootstrap or synchrotron current drive mechanisms are possible. For the present study we assumed that 40% of the plasma current comes from the bootstrap current, and 50% is provided by synchrotron drive mechanisms. The external current drive efficiency was assumed to be 0.2 amp/watt and the auxiliary power was costed at 2.25 $/watt.[21]

In an attempt to reduce the plasma current the aspect ratio was varied from 2.5 to 4.0 (see Figure 3). Increasing the aspect ratio from 2.5 to 4 caused only a 10% increase in the COE.

TECHNOLOGY CONSIDERATIONS

When assessing the Apollo-L reactor design one finds that there are four technological features which need to be discussed. These are:

- **High field (20 T) S/C TF coils**
- **High heat flux on FW wall and divertor plates**
- **Direct convertor rectenna**
- **Low radiation damage**

High Field Superconductors

Recent work at MIT[26] has shown that Ti modified Nb_3Sn wires have been fabricated which produce 20.5 T at a current density of 10,000 A/cm^2. In fact the progress in this area has been phenomenal in the past 6 years. Figure 4 shows how the high field properties of this material have been recently improved.[27] In the early 1980's it was conventional wisdom that the maximum usable field with Nb_3Sn at 4.2 K carrying 10^4 A/cm^2 was ~ 15-16 T. However, powder

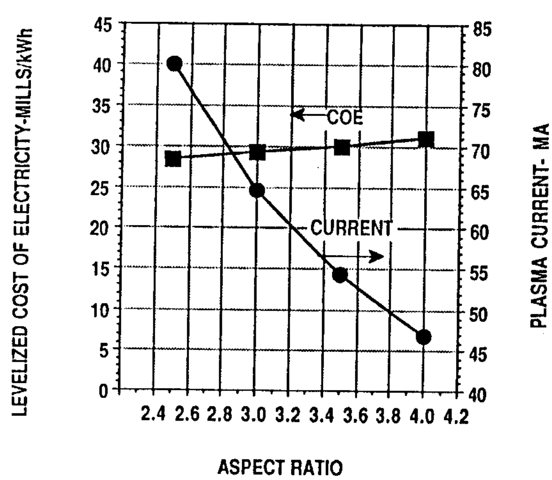

Fig. 3. Effect of aspect ratio on the levelized cost of electricity and plasma current in the Apollo-L D-He-3 reactor (1200 MWe, 85% CF, partial nuclear grade).

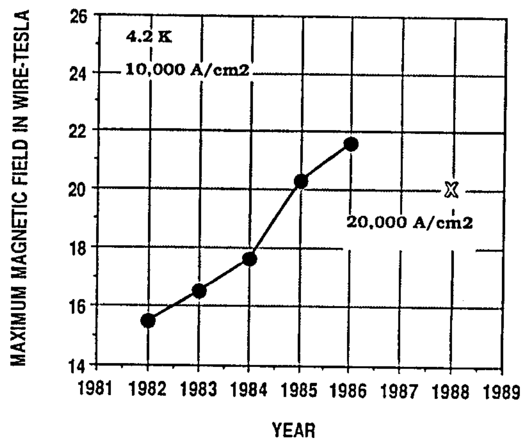

Fig. 4. Progress in high field Nb_3Sn superconductors at MIT (20,26).

metallurgical techniques have pushed that limit up by more than 1 tesla per year and in 1987 samples were fabricated[27] that carried 20,000 A/cm^2 at 4.20 K and 20 T. Since Apollo-L would not be constructed for at least 20 years, the choice of a 20 T coil does not appear to be unduly optimistic. In fact it is quite possible that even higher fields (i.e. 24 T) might be attainable in the Apollo time frame.

Heat Flux Considerations

The reduction in neutrons means that we must handle approximately 4 times more heat on the first wall than in a DT cycle. Table 2 reveals that there will be approximately 90 W/cm^2 that must be handled. The average heat on the divertor plates is on the order of 200 W/cm^2. Some perspective on these heat loads can be gained from Figure 5 where the heat fluxes in STARFIRE,[28] ITER,[29] and TITAN[30] are compared to Apollo. It is obvious that these

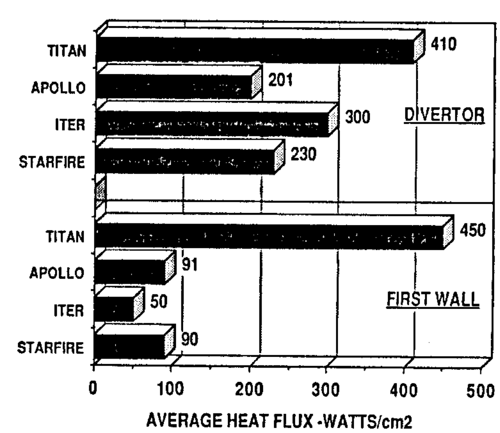

Fig. 5. Summary of average heat fluxes to the first wall and divertor zones of recent toroidal reactor designs.

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 very attractive.[31] The synchrotron radiation, which escapes from the plasma at high frequency (typically beginning at over 2500 GHz), 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 have not yet been demonstrated.

Radiation Damage to Structural Materials

For over 20 years the problem of finding a first wall which could last for the life of a DT fusion power plant has been addressed. Early analyses predicted a lifetime of 2 MW-y/m^2 from austenitic steels and recently it has been hoped the ferritic steels might extend this to above 10 MW-y/m^2. However, even a 10 MW-y/m^2 is inadequate when fusion reactor first walls will experience over 100 MW-y/m^2 in 30 FPY's. The solution has been to design for frequent change-out of the components inside the reactor which results in increased down time, increased volume of radioactive waste, increased radiation exposure to workers and an increase in the probability that new welds will fail.

Apollo presents an entirely different picture. 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, unique helium embrittlement effects so typical of high temperature DT operation are not present. One can even test candidate steels in lower temperature fission reactors to gain design confidence.

The above situation is contrasted to that of TITAN and STARFIRE in Figure 6. Here we see that the full first wall life exposure to the STARFIRE first wall is over 1,000 dpa (10 dpa ≈ 1 MW-y/m^2) at temperatures over 700°C. The TITAN first wall is exposed to over 5,000 dpa (~ 500 MW-y/m^2) at 500°C. Since current reactor designs hope that the first walls will last 10-20 MW-y/m^2, a long and costly materials irradiation program will be required before DT reactors can be commercialized.

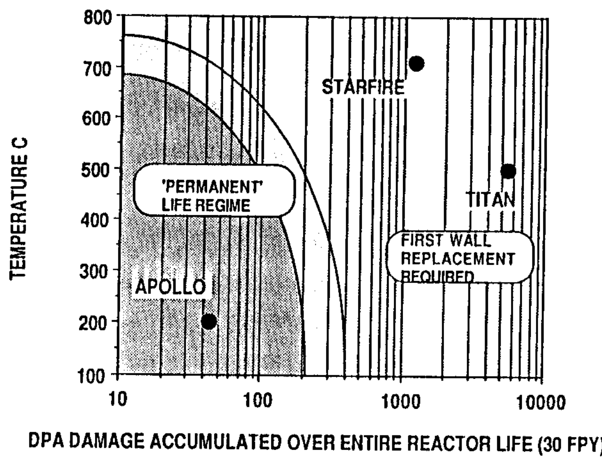

Fig. 6. Comparison of the maximum operating temperature and the radiation damage accumulated over the entire lifetime in structural components of recent toroidal fusion reactor designs. The 'permanent' lifetime regime is only an approximate estimate based on limited data.

ECONOMIC ANALYSIS

At this early stage of D-He-3 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, pinpoint areas for improvement. The Generomak[21] cost code was used to be able to compare to the ESECOM[18] study of DT power reactors. The details of that code are described elsewhere and we used the unit costs contained in this code.

The first surprising result of this work was obtained when analyzing the cost of electricity of a reactor which converts only the synchrotron radiation directly to electricity (η = 80%) by the use of rectennas. The rest of the thermonuclear and injected power (20-40 MW) is completely discarded to a cooling tower and none of the neutron, bremsstrahlung or divertor power is recovered. This case, chosen also by Logan for ESECOM,[18,31] is referred to hereafter as Apollo-LS and is compared to the case where the thermal energy is converted to electricity via an advanced steam Rankine cycle with η = 40% (this is referred to as Apollo-LT). Typically, 55% of the energy is emitted as synchrotron radiation in Apollo-LS and 45% is synchrotron radiation in Apollo-LT.

The two different approaches have far more than economic implications; the largest difference being the need to run the first wall and part of the shield at a high temperature in the thermal conversion design to achieve as

Table 3. Key Economic Factors for Apollo-L Design

Parameters Costs-M$ (1986)*	Apollo-LTW	Apollo-LTS	Apollo-LSW	Apollo-LSS	Apollo-LSS
	Aspect Ratio=2.5				AR=4
Magnets	281	296	366	394	668
Reactor Components	206	151	248	182	126
Reactor Building	221	228	188	200	212
Turbine Plant and Direct Conversion	248	242	184	187	175
Electric Plant	151	149	75	76	73
Other Reactor Plant Equipment	102	104	122	126	126
Heat Transfer	156	151	36	36	36
Miscellaneous	38	38	30	30	29
Total Direct	1402	1357	1250	1231	1444
Indirect Cost	421	407	375	369	433
Contingency	274	265	244	240	282
Overnight Cost	2097	2028	1869	1841	2159
Total Direct Capital Specific Power Cost $/kWe (w/o Contingency)	1151	1150	1064	1029	1199
COE-mills/kWh**					
• Nuclear Grade, 75% CF	42.5	42.0	42.6	40.7	46.1
• Partial Nuclear Grade, 75% CF	34.3	34.4	32.4	31.5	34.6
• Nuclear Grade, 85% CF	-	-	38.1	36.4	41.2
• Partial Nuclear Grade, 85% CF	-	-	29.1	28.3	31.0

*For partial nuclear grade construction
**See Table 2 for corresponding physics parameters

high an efficiency as possible. Other major factors include the additional turbines, associated piping, heat exchangers and buildings needed for Apollo-LT.

When the two concepts were optimized to give the lowest COE, it was discovered that there was essentially no significant economic difference as to whether or not one recovers the thermal energy (see Table 2). This simply means that extra costs for higher synchrotron radiation fraction (i.e. running at higher ion temperatures) and the additional cost of electrical conversion equipment for a lower efficiency are both of equal economic importance. On the one hand, the physics requirements of Apollo-LS are more difficult (including a higher plasma current) and, on the other, the technological requirements of Apollo-LT are more difficult (higher structural temperatures, pressures, and many more components which could fail thus lowering the availability of the power plant).

The roughly equal COE's are calculated with equal capacity factors (75%) but one can argue that the solid state rectenna units should not be subject to as frequent failure rates as high pressure steam systems and the availability of Apollo-LS should be higher. Because the turbine and the high temperature, high pressure heat transport part of a power plant typically contributes about 10% to the reduction in the capacity factor, we have chosen 85% as the value for Apollo-LS. This allows the COE of the synchrotron conversion design to be ~ 10% less than that of Apollo-LT.

The next variant considered was to replace the high performance tungsten shield on the inboard side with a steel shield. The resulting reactor is also described in Table 2 and a cost breakdown of the Apollo-LSS (the last "S" stands for steel shield versus a W shield in the high performance design, i.e. Apollo-LSW) is given in Table 3. It was found that the cost of the

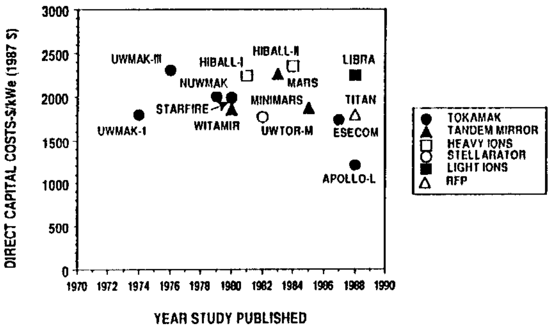

Fig. 7. Trend in direct capital costs of a wide range of magnetic and inertial confinement fusion reactor designs. Note that the only D-He-3 design is Apollo-L.

shield could almost be cut in half by replacing the tungsten in the high performance shield with steel. Later it will be apparent that this replacement also reduces the decay heat resulting in a safer design.

A capital cost breakdown of several versions of Apollo-L is given in Table 3 and the best value is compared to other magnetic and ICF fusion reactor designs in Figure 7.[32] It is obvious from the figure that Apollo-L compares very favorably to past tokamak, mirror, stellarator, RFP and ion beam fusion systems. In fact, it appears that because of the safety credits that can be attributed to a D-He-3 system, it may truly represent the first time a fusion power plant could compete directly with a fission plant.

A comparison of the Apollo-LSS design with partial nuclear grade construction costs to the base DT case (V/Li) of the ESECOM study is given in Figure 8. Both direct capital cost values are exclusive of any contingency values. There are several interesting observations to make from Figure 8. First, the difference in toroidal field (20 T in Apollo vs. 10 T in the ESECOM Base Case) is enough to override the lower power density of the D-He-3 cycle to only produce a slightly larger reactor (R=8.0 m for Apollo and R=5.9 m for the ESECOM study). Secondly, the higher field TF coils (using the optimistic scaling relationships from the ESECOM[18] study) cost 3 times that of the lower field coils. 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 40% lower than from a DT tokamak (i.e., 31 vs. 53 mills/kWh).

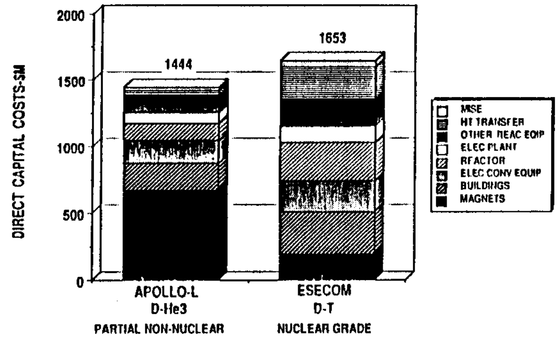

Fig. 8. Comparison of the direct capital costs of two 1200 MWe tokamak designs. Both calculations use the same costing code with the major difference being the use of direct conversion and only partial nuclear grade materials used in Apollo-L (aspect ratio = 4.0 case).

The cost of fuel for the Apollo-L reactor series was assumed to be 200$/g, roughly twice that assumed in the ESECOM[18] study. However, even at that cost, the COE of Apollo-LSS is ~ 31 mills/kWh (see Figure 9). Raising the cost of helium-3 to 1000$/g would still allow Apollo to compete economically with conventional DT systems. The projected cost of He-3 from the moon is now the subject of an extensive study at the University of Wisconsin. Future studies on Apollo will attempt to reduce the COE even further because of the low hazard potential associated with the D-He-3 fuel cycle.

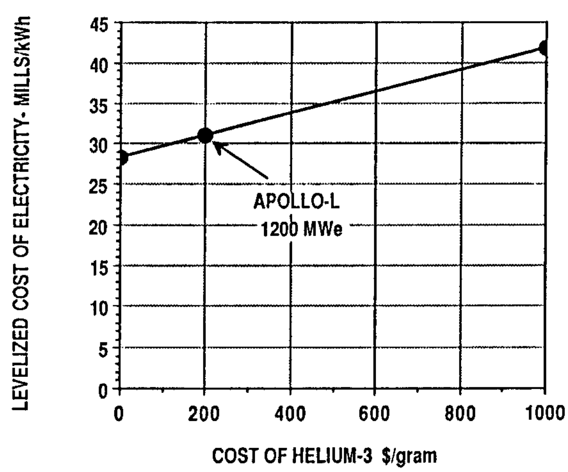

Fig. 9. Impact of He-3 costs on the levelized cost of electricity in Apollo-L at an aspect ratio of 4.0. The reference case used a value of 200 $/g.

SAFETY AND ENVIRONMENTAL FACTORS

There are 3 main areas where the D-He-3 Apollo power plant has very attractive safety and environmental features compared to DT fusion power plants:

- **Low level radioactive wastes after decommissioning.**
- **Inherent safety due to extremely low decay heat.**
- **Extremely low tritium inventory.**

A brief discussion of these advantages is given below for the AR=4 Apollo-LSS design.

Low Level Wastes

The high manganese austenitic stainless steel, Tenelon, has been used for the first wall and vacuum vessel structure as well as for the shield. Neutronics calculations made with the one-dimensional code ONEDANT[33] and radioactivity calculated with DKR[34] were used to determine the total radioactivity as a function of operating life and decay after shutdown. The neutron wall loading was determined by the NEWLIT code.[35] Details will be reported later[36] but the key results are given in Table 4. The Waste Disposal Ratings (WDR) for the first wall, inboard and outboard shields are given as a function of the discharged components. The calculations are performed at 1 year after shutdown to let the short lived isotopes decay.

Table 4. Waste Disposal Rating of Apollo Shields After 30 FPY's of Operation

	Waste Disposal Rating[a] (Γ=0.1 MW/m^2)	
Configuration	Class A[b,c]	Class C[b,c]
Inboard Shield Alone	0.94	0.05
Outboard Shield Alone	0.81	0.05
Inboard + Outboard	0.85	0.05

a) When WDR is < 1 for a given class, it can be disposed of under the regulations for that class. When WDR is > 1, it does not qualify for that level of waste and must be included in the next most restrictive waste category.

b) Class C waste must be monitored for 300 years and buried 3 m below the surface. Other restrictions on the container integrity found in Ref. 37.
Class A can be buried 1 m below surface with minimal restrictions on the container.

c) NRC-10CFR61 Limits[37]

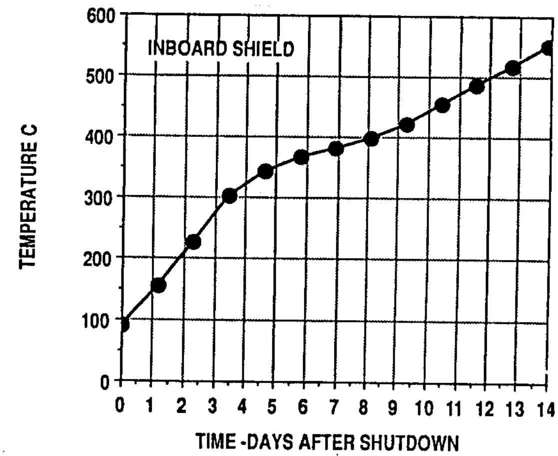

Fig. 10. The adiabatic temperature increase in the inboard shield of the Apollo-L in the event of a LOCA. Realistic conduction, convection and radiation losses would keep the maximum increase to ~ 400°C or less.

The main conclusion that one can draw from these calculations is that after a full reactor lifetime the Apollo-L structure can be disposed of as low level wastes. The material easily qualified for Class C and, in fact, qualified for Class A waste with a small amount of dilution.

Inherent Safety

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. After the plasma is turned off (in this study we used 10 s plasma operation without coolant), the decay heat is assumed to be absorbed adiabatically without any active (i.e., electrically or mechanically induced) systems to dispose of the energy generated by radioactivity. Figure 10 shows how the average shield temperature varies with time as calculated by the ATHENA[38] code under such strict conditions. The initial operating temperature ranges from a high of 230°C at the first wall to about 100°C at the back of the shield. Immediately after the plasma is turned off the first wall drops to the shield ambient (~ 100°C) temperature and stays within 50°C of that temperature for the first day. After 1 week the average temperature is still less than 400°C, and by 2 weeks of no active action, the temperature is less than 550°C. Such temperature increases will not cause any major damage to the shield. Eventually, thermal radiation to the building surrounding the reactor and convection of the atmosphere in the reactor hall will cause the temperature to asymptotically approach a value in the 400-500°C range.

Tritium Inventory

Even though tritium is not an integral part of the fuel cycle, it is produced in Apollo as the result of DD reactions. Table 5 lists the inventory of tritium as a result of 1) deposition in the fuel cleanup cycle, 2) implantation in the walls, and 3) diffusion into the shield and divertor coolant streams. The total inventory is 22 grams.

The net loss of tritium from the D-He3 (1:1.3 ratio) plasma is 24 g/full power day. This number represents the difference between the T_2 produced and T_2 burned in the plasma and is the amount of T_2 that either ends up in the fuel exhaust and cleanup cycle or diffuses into the reactor's coolant.

Table 5. Key Tritium Parameters in Apollo-L

	Grams
Production Rate	
Total produced	40.6/d
Net Loss from Plasma	23.9/d
Burned in Plasma	16.7/d
Inventory	
First Wall + Tiles	~ 0.03
Divertor Plates (4 y life)	2
Coolant Water	
• Shield + FW	10^{-3}
• Divertor	11
Plasma Exhaust and Reprocessing	9
Total	22

The T_2 which will be most difficult to contain in the event of an accident will be that in the coolant water. This 22 g could be released in the event of a pipe break and could, under the worst meteorological circumstances, result in an exposure of ~ 1 Rem to a member of the public at the site boundary. Such a value is not an acute hazard but ways of reducing that number should be pursued.

CONCLUSIONS

The preliminary design of the D-He-3 fusion reactor, Apollo, has revealed several promising features which will reduce the potential COE and increase the attractiveness of fusion. The significant reduction in neutrons allows a realistic permanent first wall to be designed and it can result in an inherently safe reactor. The cost of electricity savings (based on the Generomak code and ESECOM assumptions) appears to be ~ 40% compared to DT tokamak reactors. Areas that need to be researched in more detail include the rectennas for direct conversion of synchrotron radiation, and the operation of large 20 tesla TF coils. The moderately large plasma current associated with a low aspect ratio device represents perhaps the greatest technical challenge. However, the rewards are great and research in the next decade should reveal how soon an Apollo type reactor could provide economical electrical energy in the 21st century.

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