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**AN EVALUATION OF POLARIZED FUELS IN A
COMMERCIAL DEUTERIUM/TRITIUM TOKAMAK REACTOR**

by

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SYMBOL LIST

R_o	Major radius
A	Aspect ratio
κ	Elongation
$\overline{T}_i$	Central ion temperature
α_n	Density profile
α_T	Temperature profile
$\overline{n}_e$	Average electron density
β	Toroidal beta
B_m	Toroidal field at coil, maximum
B_o	Toroidal field at plasma center
I_o	Plasma current
P_h^{CD}	Plasma heating power for the current driver
P_e^{CD}	Electrical power required for the current driver
U^{TFC}	Magnetic energy in toroidal field coil
W_n	Average neutron wall load
P_f	Fusion power
P_{net}	Net electric power
L^{TFC}	Mean perimeter of a toroidal field coil
$\Delta_{B/S/V}^1$	Inboard blanket/shield/vacuum distance
R_1	Mean radius of inner coil leg
R_2	Mean radius of outer coil leg
H_{max}	Half the height of the toroidal coil measured at midpoint
$N^{TFC} I^{TFC}$	Total ampere turns
Δ_{TFC}	Toroidal field thickness
U_{free}	Total energy in the plasma
σ	Fusion reaction cross section

m_{Cu}	Mass of copper in toroidal field coils
m_{SS}	Mass of stainless steel in toroidal field coils
m_{Ti}	Mass of titanium in toroidal field coils
m_{Sn}	Mass of tin in toroidal field coils
m_{He}^{TF}	Mass of helium vessel for magnets
m_{VT}^{TF}	Mass of vacuum tank around magnets
m_{sp}	Mass of shear panels for restraining magnets
U^{EF}	Magnetic energy in equilibrium field coils
$(P_h^{CD} - 75)$	Current driver power needed other than at startup

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ABSTRACT

The use of polarized fuels in commercial deuterium-tritium tokamak fusion reactors has been assessed. Some of the advantages cited for this fueling modification have been evaluated. Although the advantages are real, their magnitude is such that polarized fuels do not appear to be a significant factor in increasing the attractiveness of commercial reactor designs.

I. INTRODUCTION

The advantages cited for using polarized fuel in magnetic fusion reactors are: 1) an increase in plasma reactivity of about 50%^(1,2); 2) the ability to control the spatial distribution of the neutrons produced⁽¹⁻⁴⁾; and 3) reduced capital⁽⁵⁾ or operating costs. Increased reactivity may also relax ignition and energy breakeven requirements.⁽⁴⁾ Controlling the spatial neutron distribution could decrease first wall radiation damage, shield thickness, or improve the tritium breeding ratio. Reduced capital costs would result from smaller magnets, smaller radiofrequency systems, and thinner shields.

The goal of this study was to provide a limited analytical assessment of the technical and economic benefits associated with the use of polarized fuels in a commercial deuterium/tritium tokamak fusion reactor. The effort was focused on determining key benefits accrued in the reactor systems. The balance of plant was assumed to not be appreciably affected.

The deuterium-tritium system was chosen since it is likely to be the fuel cycle of the first commercial fusion reactor system. In addition, the feasibility of using polarized fuels to eliminate neutrons as a product in other fusion reactions, e.g. deuterium/helium-3 and deuterium/deuterium has been questioned.⁽⁶⁾

We made four assumptions: First, 100% polarization is achieved which represents an optimistic assumption. Second, the technology for producing polarized fuels will exist in the commercial reactor time-frame. Third, necessary wall materials will be available. Fourth, reactor components will be modular to simplify maintenance.

Two types of reactors were considered: one was the STARFIRE⁽⁷⁾ reactor which has a moderate beta, a moderate radius, and a moderate magnetic field, and the other was an advanced reactor developed in ANL's Tokamak Power Systems Study⁽⁸⁾ which has a higher beta, a smaller radius, and a lower magnetic field. Since the physical size, i.e., major radius of a reactor, significantly affects the cost of the toroidal field magnets, these two systems should provide a means of separating the size effect from effects attributable to the use of polarized fuels. Some selected parameters for these two cases are shown in Table I-1.

Table I-1. Selected Parameters of STARFIRE Reactor and an Advanced Reactor With High Beta

Parameter	Unit	STARFIRE	Advanced Reactor
R_O	m	7.0	5.25
A		3.6	6.0
κ		1.6	2.0
$\overline{T}_1$	keV	24.1	25.9
α_n		1.1	0.3
α_T		0.3	1.1
$\overline{n}_e$	10^{20} m^{-3}	1.18	1.77
β		0.067	0.25
B_M	T	11.1	6.0
B_O	T	5.8	3.83
I_C	MA	10.1	3.99
P_h^{CD}	MW	90.4	80
P_e^{CD}	MW	152.7	145
U^{TFC}	GJ	50	5.0
W_n	MW/m ²	3.6	3.4
P_f	MW	3510	1275
P_{net}	MW	1200	540

Note: All symbols are given in Symbol List at beginning of document.

Within the body of the report, Section II examines the two scientific feasibility issues: 1) preparation and introduction of polarized fuel; and 2) the effect of the expected depolarization mechanisms. In Section III, the impact of polarized fuels on plasma engineering and on neutronics are assessed. Section IV expands on the implications of the use of polarized fuels in some of the reactor systems - radiofrequency heating/current drive systems, impurity control system, and materials and maintenance. The overall benefits of polarized fuels are summarized in Section V. Recommendations of future work are made in Section VI.

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II. SCIENTIFIC FEASIBILITY

II.A Polarized Fuel: Production and Fueling

Two problems are envisioned in the use of polarized fuel in commercial fusion reactors. One is the production of the quantities needed [$\sim 4\text{--}12 \times 10^{21}$ molecules/s (1270 - 3510 MW fusion power)] for a plasma with a fractional burn of $\sim 10\%$. The second is the introduction of the fuel into the core of the plasma so that depolarization of the fuel at the wall of the plasma chamber is minimized.

Three different methods have been proposed for the production of polarized deuterium and tritium fuel. They are: 1) optical pumping⁽¹⁾ to generate gaseous atomic polarized species; 2) polarization of atomic species in a magnetic field followed by condensation in a cryogenic system^(2,3); and 3) conversion of the solid, unpolarized molecular species to the polarized species via relaxation in a cryogenic magnetic field.⁽⁴⁾ Current work⁽¹⁻⁴⁾, with the exception of Souers⁽³⁾, is focused on the hydrogen or deuterium species.

II.A.1 Optical Pumping

Using the optical pumping method,⁽¹⁾ a 65% polarization fraction has been achieved at a hydrogen atom density of 10^{12} cm^{-3} with a non-ideal wall material. The near term achievable goal is $\sim 90\%$ polarization fraction with a hydrogen atom density of 10^{16} cm^{-3} . With deuterium, there is a factor of two lower efficiency in polarization transfer due to the deuterium hyperfine atomic structure. With tritium, $\sim 90\%$ polarization could be expected. The equipment currently used with this method is a radiofrequency field to form gaseous atoms, a magnetic field to provide Zeeman splitting of the polarizing source (^{85}Rb), and a laser pumping system.

Some of the requirements for an optically pumped system are:

- 1) The spin exchange rate, R_{SE} , has to exceed the hydrogen relaxation rate, γ_H , in order to maximize the polarized hydrogen spin population, S_H .

$$R_{SE} = [Rb] \nu \sigma_{SE} > \gamma_H \quad (\text{II.A-1})$$

$$S_H \sim \frac{R_{SE}}{R_{SE} + \gamma_H} \cdot S_R \quad (\text{II.A-2})$$

where v = the relative velocity ($\sim 10^5$ cm s⁻¹), σ_{SE} = the spin exchange cross section between paramagnetic species ($\sim 10^{-14}$ cm²), S_R is the polarized rubidium spin population, and $[Rb]$ is the rubidium atom density ($10^{11} \rightarrow 10^{13}$ cm⁻³). For a system with specially coated/treated walls, $\gamma_H \sim 1$ s⁻¹. For other wall materials, $\gamma_H \sim 100$ s⁻¹ which is unacceptable. Thus, with coated/treated walls $S_H \sim 0.999 S_R$; without coated walls $S_H \sim .909 S_R$.

2) To account for volume relaxation of the polarized species due to spin flip collisions and spin orbit interactions, the ratio of the hydrogen to rubidium densities is:

$$\frac{[H]}{[Rb]} < \frac{\sigma_{SE}}{\sigma_D} \sim 10^7 \quad (II.A-3)$$

where σ_D = the cross section for depolarization due to volume relaxation, and is $\sim 10^{-21}$ cm². Thus the hydrogen atom density, $[H]$ is less than $10^{17} \rightarrow 10^{19}$ cm⁻³ for 99% polarization of $[Rb]$ of $10^{11} \rightarrow 10^{13}$ cm⁻³.

3) The laser power must be greater than the sum of the depolarization rates from all mechanisms. If the relaxation rate due to wall collisions for rubidium and hydrogen are both low, then spin flips in the vapor is the major depolarization route. The laser photon intensity is:

$$I > [H]^2 V v \sigma_D \quad (II.A-4)$$

where V is the volume of the production device. For $V = 50$ cm³ and a laser generating 1 watt/cm², and $[H] \leq 7 \times 10^{16}$ /cm³, the photon flux⁽¹⁾ is 4×10^{18} photons/s.

To achieve the desired fluxes needed to fuel a commercial reactor, we need two laser sources (one for tritium and one for deuterium) each 5000 times more powerful than the one described above, i.e. two 5 kwatt (5 kJ) lasers which can be operated continuously. This compares with the currently available 10 kJ lasers which require ~ 5 minutes between shots.

Since the laser system is the major component in this system, we have assumed that the lasers which this technique requires will be developed in the 21st century. We have a speculative cost for these lasers,⁽⁵⁾ $\sim \$2-5$ million

per kJ. For a 1270 MW_f reactor, the capital cost for 10 kJ of lasers is expected to be \$20 M to \$50 M. For a 3510 MW_f reactor, the capital cost for 27 kJ is expected to be \$55 M to \$130 M. Each of these lasers is anticipated to be the size of a small room.

It is possible that a more efficient and less costly system can be developed if intense Lyman alpha light sources and polarizers which can directly polarize hydrogen species are developed. This is a research area which is not presently under development.

The polarized atomic species are introduced close to the plasma core to avoid depolarization at the plasma edge. Therefore only certain injection techniques are acceptable: 1) injecting fuel pellets formed after condensing the polarized atoms, and; 2) injecting the atomic gas via neutral beams. The use of cryogenic pellets should not introduce appreciable capital costs since the fusion plant has a large cryogenic capacity.

However, if neutral beams are required, an additional capital cost is incurred. This can be substantial since the capital cost of neutral beams is \$2-\$10/watt.^(5b) At \$2/watt, introduction of 600 Amp of polarized D and T atoms continuously into a reactor (1270 MW_f) at 20 keV, would have a capital cost of \$24 M. At the higher unit cost, \$10/watt, the capital cost would be \$120 M, which makes this technique unacceptable.

If a neutral beam can be used both to generate the polarized species and to introduce them into the reactor, the total cost could be reduced. Kaplan⁽⁶⁾ has designed a negative neutral beam which produces fully polarized negative deuterium ions. However the polarized beam intensity is less than 10% of the initial starting intensity. The gas efficiency is $\leq 10\%$; therefore, the recirculating power fraction is expected to be fairly high. To be useful, this system will have to be improved.

II.A.2 Cryogenic Techniques

One technique proposed for producing spin polarized hydrogen is to place atomic hydrogen held at 0.3 K into a 5-10 tesla magnetic field. Microwaves are then used to form nuclear polarized molecules. This technique is being examined both by Kleppner⁽⁴⁾ with hydrogen and deuterium and most recently by Souers⁽³⁾ with deuterium and tritium. The main capital cost items are the

refrigerated cell and the magnet system required to produce 4×10^{21} molecules/s. Current ~ 6 T magnets cost between \$2 M and \$10 M depending on the bore size. Other systems might cost an additional \$5 M. If DT polarized molecules are produced, they will have a limited lifetime even at 21 K due to radiation damage. The $1/e$ lifetime is 150 hr;⁽³⁾ depolarization occurs after a minute making long term storage of this species infeasible.

For injection into the plasma, the polarized molecules have to be formed into pellets. The major problem foreseen is depolarization of the polarized species due to interaction with wall materials while the pellet is being formed. This is an area of research that needs investigation.

A second technique, which is successful in producing spin polarized deuterium,⁽²⁾ is to allow pure ortho- D_2 to relax to a polarized state in a cryogenic magnetic system. To reduce the time required to obtain equilibrium, hydrostatic pressure⁽²⁾ can be used. The overall reaction time may be excessive for tritium species even with this modification. Therefore, an alternate technique, the atomic cryogenic system mentioned above, is probably more useful with tritium. Recently,⁽⁶⁾ Honig has suggested a new concept for producing tritiated species but no experiments have yet been done.

The second technique (molecular species plus cryogenic system) has a low capital cost ($< \$5$ M); however, it is not anticipated to be useful in producing tritiated polarized species. The fueling techniques which would be used with material produced from this technique are those previously cited, pellet fueling, or neutral beam injection. In the latter type of fueling, the solid polarized fuel could serve as the target.

II.A.3 Conclusions

The scientific feasibility of producing polarized deuterium has been shown.⁽⁶⁾ An experiment⁽³⁾ is currently in progress to produce polarized deuterium tritium (DT). Thus, the main question is one of economics, e.g., what capital cost is required to produce $4\text{--}12 \times 10^{21}$ molecules/s and to subsequently put it into the core of the fusion reactor. A summary of the anticipated costs is shown in Table II.A-1. The best fueling system from the capital cost standpoint would use pellet injectors and the cryogenic/microwave technique. The additional capital cost of using polarized fuel based on this system is $< \$15$ M for the 1270 MW_f reactor and $< \$30$ M for the 3510 MW_f reactor. For an optical pumping, neutral beam injection system, the capital cost could exceed \$34 M and \$107 M for the two cited reactors.

Table II.A-1. Anticipated Capital Costs for Fueling with Polarized Fuel

Fusion Power	Capital Cost (\$M)	
	1270 MW	3510 MW
Technique: Production		
Optical pumping ^a	20-50	55-130
Cryogenic/microwave	7-15	<30
Cryogenic (D ₂)	< 5	< 5
Technique: Fueling		
Pellet injectors (reference)	10	20
Neutral beams	24-120	72-360
<u>Total Minimum Increment</u>	< 15	< 30
Cryogenic/microwave		
Pellet Injectors		
<u>Total Maximum Increment</u>	> 44	> 127
Optical pumping		
Neutral beams		

^a \$2 M - 5 M/kJ; 10 kJ for 1270 MW; 27 kJ for 3510 MW.

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II.B. Depolarization Mechanism

There are three major pathways whereby polarized deuterium and tritium molecules can be depolarized: plasma interactions, radiofrequency interactions, and materials interactions. Each of these areas have been evaluated.⁽¹⁻⁵⁾ This section summarizes the major problems noted and the possible solutions.

II.B.1 Plasma Interactions

The mechanisms for depolarizing nuclei in the plasma⁽¹⁻³⁾ are all weak and are due to four effects: 1) static externally produced inhomogeneities in the magnetic field; 2) binary collisions between particles; 3) magnetic fluctuations in the plasma, and; 4) atomic effects.

1) A nucleus with velocity, v , passing through static magnetic field inhomogeneities of scale, s , sees them at a frequency v/s . Frequencies below the nuclear precession frequency do not change the polarization. The deuteron and triton precession frequencies are:

$$\Omega_2 = \frac{g_2 e B_0}{2m_p c} ; \quad \Omega_3 = \frac{g_3 e B_0}{2m_p c} \quad (\text{II.B-1})$$

where g_2 is the magnetic moment of the deuteron in nuclear magnetons, g_3 is the magnetic moment of the triton, a nuclear magneton $= eh/2m_p c$, and B_0 is the magnetic field. Since the deuteron cyclotron frequency is

$$\omega_2 = eB_0/2m_p c \quad (\text{II.B-2})$$

$$\Omega_2 = 0.86 \omega_2 \text{ and } \Omega_3 = 5.96 \omega_2.$$

2) The triton or deuteron can interact with electrons, other deuterons and/or tritons through spin-orbit and spin-spin interactions; the deuteron can also interact through its quadrupole moment. The depolarization rates from these interactions are quite small⁽⁶⁾ because of the very short duration of the collisions and the weakness of the interaction. This value was quantified⁽³⁾ by introducing an effective cross section σ_1 for each depolarization process. Each collision produces a randomly phased change in β , the amplitude of the undesired state. These add incoherently as

$$\frac{d (\Delta\beta)^2}{dt} = \sum_i n v \sigma_i \quad (\text{II.B-3})$$

where v is 0.6×10^{10} and n is the electron density. Values of σ_i are shown in Table II-B.1.(3)

The cross sections in Table II.B-1 are very small. Because of the factor v in Eq. (II.B-3), depolarization by electrons predominates. The overall cross section for tritons is $\sim 1.7 \times 10^{-29} \text{ cm}^2$, for deuterons it is $0.7 \times 10^{-30} \text{ cm}^2$ for those in the $m_s = \pm 1$ states, and $1.4 \times 10^{-30} \text{ cm}^2$ for those in $m_s = 0$. For a plasma with an electron density (n_e) of $\sim 2 \times 10^{14} \text{ cm}^{-3}$, $d (\Delta\beta)^2 / dt = 2 \times 10^{-5} \text{ s}^{-1}$ for tritium, $1.75 \times 10^{-6} \text{ s}^{-1}$ for $m_s = 0$ deuterium, and $0.9 \times 10^{-6} \text{ s}^{-1}$ for $m_s = \pm 1$ deuteron. For a 20 s resident time, the percent depolarization is $\sim 0.04\%$ for a triton, and 0.004% for a deuteron.

3) A moving polarized nucleus is depolarized by harmonics of the fluctuating fields which are left-circularly polarized with respect to $\vec{B}$, provided the Doppler shifted frequency is equal to the precession frequency. Depolarization by thermal fluctuation is extremely small. The main problem arises from plasma instabilities which cannot be simply predicted. For a highly non-Maxwellian plasma velocity distribution, significant depolarization can occur. The triton resonant frequency for direct interaction is $\omega_3 \sim 6 \Omega_2$. Only the left circularly polarized component of the off-angle propagating whistler wave can interact. An estimate of the depolarization produced in 20 s is 1%.(3) A similar estimate for deuterons shows that $\sim 1\%$ depolarization again occurs in 20 s. The deuteron resonant frequency, $\omega_2 = 0.86 \Omega_2$ is near the ion cyclotron wave band. In a 50:50 D/T plasma, the waves cut off below $0.833 \Omega_2$. For non-direct interactions, the Ω_2 resonance can occur for a transverse Alfvén wave at $\omega = 0.15 \omega_2$. Thus, no specific instability has been identified which appreciably reduces polarization.

4) The polarized nucleus is not depolarized by ionization; but if recombination couples the nucleus to an electron of opposite spin, there is a 50% probability that it will be depolarized. This mechanism is inhibited if the external magnetic field, B , is sufficiently strong compared to the critical field, B_c , at which Zeeman splitting equals the hyperfine splitting. The probability of spin exchange is reduced⁽⁷⁾ by $(B_c/2 B_0)^2 - (B_c = 300 \text{ gauss for}$

Table II.B-1. Cross Sections for Collisional Depolarization⁽³⁾

$$\left[r_p = \frac{e^2}{m_p c^2}, \omega_p^2 = \frac{4\pi n e^2}{m}, p_o = \frac{e^2}{T}, \lambda = \frac{h}{mv} \right]$$

Depolarization Mechanism	Cross Section	For D(cm ²)	For T(cm ²)
<u>By electrons</u>			
Spin-orbit	$4\pi g_p^2 r_p^2 \ln(c/\omega_p \lambda)/3$	1.45×10^{-30}	1.76×10^{-29}
Spin-spin	$(11/9) \pi g_p^2 r_p^2$	$.73 \times 10^{-31}$	$.81 \times 10^{-30}$
Quadrupole		7.3×10^{-38}	
<u>By deuterons</u>			
Spin-orbit	$(\pi/3) g_p^2 r_p^2 \ln(c/\omega_p p_o)$	3.7×10^{-31}	4.4×10^{-30}
Spin-spin	$(\pi/3) g_2^2 g_p^2 r_p^2$	1.1×10^{-32}	1.3×10^{-31}
Quadrupole		2.3×10^{-31}	
<u>By tritons</u>			
Spin-orbit	$(\pi/3) g_p^2 r_p^2 \ln(c/\omega_p p_o)$	3.7×10^{-31}	4.4×10^{-30}
Spin-spin	$(\pi/3) g_3^2 g_p^2 r_p^2$	1.2×10^{-31}	1.6×10^{-30}
Quadrupole		2.3×10^{-31}	

deuterium and 10^3 gauss for tritium).

Thus, multiple recombinations of atomic hydrogen to ionic hydrogen could occur in a 5 T field without significant depolarization. However, if molecular hydrogen is formed, rapid depolarization could occur due to spin orbit coupling associated with molecular tumbling. This could be minimized by the design of the region at the edge of the plasma so that recombination either in the gas phase or on the first wall surface does not occur.

II.B.2 Radiofrequency Interactions

Two cases are considered for radiofrequency interactions. The first case is a steady-state ignited plasma. Here radiofrequency (rf) interactions will be negligible once ignition is attained. For the second case, a driven plasma, only a low frequency system with a frequency 1.32 times the deuteron cyclotron frequency ($f = \frac{1}{2\pi} \left(\frac{eB}{m} \right)$) may be acceptable since higher frequency systems are likely to depolarize the polarized species.⁽⁴⁾ The systems which can be used in a rf driven reactor are described in Section IV.A.

II.B.3 Materials Interactions

In toroidal reactors, recycling at the first wall can occur a minimum of twenty times. Thus, nuclei cannot only molecularly recombine but also they can embed themselves ~ 100 Å into the first wall surface. Once there, they can diffuse back to the surface to recombine as molecules or they can be desorbed as atoms - by ion, electron and photon bombardment. An assessment of the depolarization mechanisms operable in this situation was done by Greenside, et al.⁽⁵⁾ They described the dependence of depolarization rates on material properties and the temperature of the first wall.

Various conditions have to be considered in determining which material is the best one to use in a reactor with polarized fuel. As a general criterion, Greenside suggested that the temperature and composition of the walls should be chosen so that the following equation is not satisfied,

$$\omega_o \tau_c \sim 1 \quad (\text{II.B-4})$$

where ω_o is the Larmor frequency and τ_c is the correlation time of the microscopic fluctuations in the magnetic field or in the electric field gradients

of the wall material. The Larmor frequency is defined as γB_0 where γ is the nuclear gyromagnetic ratio, $2.68 \times 10^4 \text{ rad s}^{-1} \text{ G}^{-1}$ for a proton, 0.411×10^4 for a deuteron, 2.85×10^4 for a triton, and 1.76×10^7 for an electron. B_0 is the magnetic field. Nonmetallic walls at high temperatures, where $\omega_0 \tau_c \ll 1$ would not satisfy Eq. (II.B-4). Therefore they can be considered as primary material candidates for the limiter and divertor.

For nonmetals, nearby diffusing nuclei, which are not part of the diatomic molecule on the surface, can become coupled to the wall lattice in the vicinity of the diatomic molecules. These nuclei can then rapidly depolarize. This relaxation mechanism has been suggested⁽⁸⁾ to be dominant for both deuterium and tritium in hydrogenated amorphous semiconductors below 300°C . Thus, it is likely to play a role in the depolarization of plasmas by nonmetallic walls.

Since there are several depolarization mechanisms operative in a metal, the expected depolarization is not a simple process. For electronic relaxation,

$$T_{le} T = \kappa \quad (\text{II.B-5})$$

where T is temperature and κ is the Korringa relation⁽⁹⁾ which is independent of temperature and the external magnetic field B_0 . The electron depolarization rate increases with increasing temperature. However, hydrogen covered metal surfaces are not strong depolarizers if there is no surface concentration of paramagnetic impurities. The hydrogen species (D and T) form strong localized bonds with nearby metal atoms. This leads to a reduced density of conduction electron states and a longer relaxation time. Since the reflection probability is large ($>90\%$) for low energy ions and neutral atoms ($< 10 \text{ eV}$), a metallic wall may be acceptable for low enough plasma edge temperatures.

For diffusion dominated processes, several effects have to be considered. The longitudinal relaxation time is smallest for temperatures (T_d) where

$$T_d \approx - \frac{E_{act}}{k_b} \left[\ln \left(\frac{\omega_0 \tau_0}{2} \right) \right]^{-1} \quad (\text{II.B-6})$$

Here ω_0 is the Larmor frequency, E_{act} is the activation energy which depends on the local configuration of chemical bonds, and k_b is the Boltzman constant. A prominent minimum in T_1 as a function of temperature is evidence that depolarization is dominated by diffusional motion. For transition metal hydrides,⁽¹⁰⁾ there is a minimum in T_1 near 333 K but above 500 K, diffusion is so rapid that other depolarization mechanisms dominate (Korringa, paramagnetic impurities).

For nonmetals the ideal temperature from diffusional considerations depends on the trap density and the distribution of trap energies. Very high temperatures may result in other material problems (erosion, sputtering). High operating temperatures can help reduce⁽¹¹⁾ depolarization of deuterium nuclei by quadrupole relaxation since rapid diffusion can tend to zero out depolarization except at the surface. At surfaces, however, depolarization rates of $\sim 0.1 \text{ s}^{-1}$ are possible,⁽¹²⁾ which makes quadrupole relaxation a significant depolarization source even at high temperatures.

Paramagnetic impurities are the major source of depolarization for nonmetals. The useful temperature range for a material will depend on the type of impurity present and the type of host lattice. Impurity levels will have to be kept $< 10 \text{ ppm}$ as shown by recent studies.⁽¹⁰⁾

Depolarization by wall materials is a critical issue for the use of polarized fuel. The only method that can provide an answer to our many unanswered questions on the appropriate material and temperature is the measurement of T relaxation rates under fusion relevant conditions.

In Sections IV.B and IV.C, other first wall problems not related to depolarization are examined.

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III. REACTOR IMPLICATIONS

III.A Introduction

To provide a good overview of the benefits of polarized fuel in a tokamak commercial fusion reactor, a large reactivity parameter space has been examined. Examples of both the first and second stability plasma regimes were evaluated. The first stability regime uses the STARFIRE design as a reference and then considers a lower magnetic field, a lower beta and a higher plasma temperature. The basis of the second stability regime is work currently being done in ANL's Tokamak Power Systems Study. A reference case is given. Then five alternatives of the reference case (lower magnetic field, lower beta, higher plasma temperature, higher wall load, and smaller size) are assessed. The results are found in Section III.B.

The benefits of neutron directionality were determined using 3-D neutronic calculations. These results are in Section III.C.

III.B Benefits of Polarized Fuels to Plasma Engineering

III.B.1 Tokamak in the First Stability Regime - STARFIRE

The main benefit to plasma physics occurs for parallel polarization of the D and T ions. If the fusion cross section for randomly polarized ions is σ_0 , then the parallel polarized ions achieve a cross section⁽¹⁾ $\sigma = 1.5 f \sigma_0$, where $0.95 \lesssim f \lesssim 1.00$. We set $f \equiv 1$ in what follows. The fusion reaction rate, $\langle \sigma v \rangle$, is found by averaging over Maxwellian ion distributions and is a function of the local ion temperature, T_i . A useful approximation to the tokamak's fusion power output is given by⁽²⁾

$$P_f \approx 6\pi^2 \frac{R_o^3}{A^2} \frac{\beta^2 B_o^4}{64 \mu_o^2} \frac{E (1+\alpha)^2 H}{T_{i0}^2} \langle \sigma v (T_{i0}) \rangle, \quad (\text{III.B-1})$$

where R_o = major radius, A = aspect ratio, B_o = toroidal field at R_o , α = pressure profile exponent (~ 1.5), β = plasma beta, $H \approx 0.07$, $E = 17.6$ MeV, and $T_{i0} = (1 + \alpha_T) \bar{T}_1$ = central ion temperature. This expression illustrates several means to take advantage of the replacement of σ_0 with $1.5 \sigma_0$. The obvious options, lower B_o , lower β , or higher T_{i0} , will be dealt with in

turn. The common plasma and magnet parameters for STARFIRE⁽³⁾-class reactors are listed in Table III.B-1. The variable parameters are in Table III.B-2.

We quantify the capital cost reductions associated with polarized fuels by using cost algorithms developed in Ref. 5. All costs are in 1983 dollars.

III.B.1.1 Benefits of Lower Toroidal Field - STAR-B

We will assess capital cost reductions associated with lower fields by comparing STARFIRE-class reactors. In Table III.B-2 the plasma and magnet parameters for a reactor, STAR-B, designed with lower B_0 and $\sigma = 1.5 \sigma_0$ are listed. Reference to Eq. (III.B-1) shows B_0 is reduced by the factor $(1.5)^{1/4} = 1.107$ if σ is increased by 1.5. This 11% reduction brings the peak field at the toroidal field coil (TFC) down from 11.1 T to 10.03 T. In an optimized TFC design the conductor is graded, and above 9 T a Nb_3Sn superconductor is used in STARFIRE; so we find that the σ enhancement is not sufficient to remove the need for advanced superconductors in STAR-B. However, the magnetic energy in the TFC is moderately reduced, by the factor $\sqrt{1.5} = 1.225$, from $U^{TFC} = 50$ GJ to $U^{TFC} = 41.6$ GJ, and we expect cost savings accordingly.

We quantify the cost savings by analyzing the reductions in materials which occurs by designing a lower field TFC set. Figure III.B-1 displays the STARFIRE design for the 11.1 T magnet. The materials inventory for the cabled conductor of the TFC is given in Table III.B-3, and the winding cost, including fabrication, is listed in parentheses. This cost algorithm⁽⁴⁾ assigns unit costs of \$34.4/kg - Cu; \$16.7/kg - stainless steel; \$118/kg - NbTi; and \$234/kg - Nb_3Sn . These are the long term prices assumed in the STARFIRE study to represent those present in a mature fusion economy. Each TFC for STAR-B carried 1.63 MA-turn less current, which is 68 turns of the 24-kA cable in the high field (Nb_3Sn) region. Materials savings amount to 40% of the Nb_3Sn , 10% of the steel and copper, and no reduction in the NbTi.

Elimination of these windings reduces the TFC thickness, Δ_{TFC} , and this reduces the perimeter of the helium vessel. The helium vessel is constructed of 4 cm thick stainless steel which is relatively expensive, \$26/kg, due to quality control required to assure leak tightness. Its mass, M_{He}^{TF} , and total cost are reduced by $\sim 5\%$ for STAR-B; see Table III.B-3.

Table III.B-1. Common Plasma and Magnet Parameters for STARFIRE and Three Alternatives Which Use Polarized Fuels

Parameter	Unit	STARFIRE/Three Alternatives
R_o	m	7.0
A		3.6
κ		1.6
α_n		1.1
α_T		0.3
P_f	MW	3510
W_n	MW/m ²	3.6
L_{TFC}	m	40
$\Delta_{B/S/V}$	m	1.40
R_1	m	3.17
R_2	m	13.0
H_{max}	m	7.06

Table III.B-2. Variable Plasma and Magnet Parameters for STARFIRE and Three Alternatives Which Use Polarized Fuels

Parameter	Unit	STARFIRE	STAR-B	STAR- β	STAR-T
σ	σ_o	1.0	1.5	1.5	1.5
$\overline{T}_i$	keV	24.1	24.1	24.1	~31
β		0.067	0.067	0.0547	0.067
B_o	T	5.8	5.24	5.8	5.8
I_o	MA	10.1	9.13	10.1	10.1
P_h^{CD}	MW	90.4	66.6	73.8	57.5
P_e^{CD}	MW	152.7	112.5	124.7	97.1
B_M	T	11.1	10.03	11.1	11.1
$N_{TFC} I_{TFC}$	MA	203	183	203	203
U_{TFC}	GJ	50	41.6	50	50
Δ_{TFC}	m	1.195	1.091	1.195	1.195
$\overline{n}_e$	$10^{20} m^{-3}$	1.18	0.963	0.963	0.751
P_{net}	MW	1200	1240	1228	1256
U_{free}	GJ	2.7	2.2	2.5	2.7

Table III.B-3. Comparison of Materials Inventory and Capital Costs for STARFIRE⁽³⁾ and Three Alternatives Which Use Polarized Fuels

Parameter	Unit	STARFIRE	STAR-B	STAR-β	STAR-T
m_{Cu}	Mg	2130 (73.7)	1941 (66.8)	2130 (73.7)	2130 (73.7)
m_{SS}	Mg	1660 (27.7)	1512 (25.3)	1660 (27.7)	1660 (27.7)
m_{Ti}	Mg	46 (5.4)	46 (5.4)	46 (5.4)	46 (5.4)
m_{Sn}	lb	5 (1.0)	3 (0.6)	5 (1.0)	5 (1.0)
m_{He}^{TF}	Mg	1342 (34.9)	1276 (33.2)	1342 (34.9)	1342 (34.9)
m_{VT}^{TF}	Mg	983 (23.6)	135 (3.2)	983 (23.6)	983 (23.6)
m_{SP}	Mg	838 (20.1)	684 (16.4)	838 (20.1)	838 (20.1)
U^{EF}	GJ	10.0 (30.5)	8.16 (24.9)	10.0 (30.5)	10.0 (30.5)
$(P_h^{CD} - 75)^a$	MW	15.4 (15.4)	---- (0.0)	---- (0.0)	---- (0.0)
Cost, polar ^b		(232.3)	(175.8)	(216.9)	(216.9)
Cost, BOP ^c		(1840.3)	(1840.3)	(1840.3)	(1840.3)
Cost, total		(2072.6)	(2016.1)	(2057.2)	(2057.2)

Note: Direct capital costs (\$1983, in millions) are given in parentheses.

^a Assumption: \$1/watt; higher cost will result in greater cost savings for three alternatives.

^b Polar: Reduction in magnet and current driver capital costs associated with the use of polarized fuel. The cost of producing polarized fuels is not included.

^c BOP: Balance of plant.

NOTE: INTERCOIL SUPPORT STRUCTURE NOT SHOWN.

Figure III.B-1. Design of 11.1 T magnet in STARFIRE. (3)

The TFC in the STARFIRE design is supported between coils at the support cylinder (inboard) and by shear panels in the outboard region. Between these locations the free span of each TFC extends 11.39 m, and this unsupported span tends to be deflected by the overturning forces imposed by the equilibrium field coils (EFC). The stiffness of the helium vessel and its surrounding vacuum tank must provide enough rigidity to limit the deflection. In STARFIRE this was accomplished by providing a substantial thickness, $t_v = 0.042$ m, to the vacuum tank structure. Treating the nested boxes (helium and vacuum tank in Fig. III.B-1) as a perfectly coupled beam⁽⁵⁾ we calculate the total moment of inertia, I , as the sum of the moments from both steel tanks, $I = I_{VT} + I_f$. For STARFIRE, with a helium tank gauge of $t_{He} = 0.040$ m and $t_v = 0.042$ m, the moment is $I = 0.23 \text{ m}^3 b_o = 0.23 \text{ m}^3 \times (1.033 \text{ m})$; this results in a vacuum tank mass of $M_{VT}^{TF} = 83 \text{ Mg}$. This steel structure is costed at \$24/kg.

STAR-B has a less expensive vacuum tank since the overturning forces are smaller. These forces are proportional to the amp-turns carried in each TFC, I^{TFC} , times the EFC field crossing the TFC. We have seen I^{TFC} is reduced by $(1.5)^{1/4}$. Moreover, MHD calculations indicate that the toroidal plasma current, I_o , is proportional to B_o at fixed β and geometry, and that the EFC field is proportional to I_o . Hence, the $(1.5)^{1/4}$ reduction in B_o translates to a $(1.5)^{1/4}$ reduction in the EFC field. In consequence, out-of-plane forces are reduced by $\sqrt{1.5}$, and, for STAR-B, the moment I can be reduced by the same factor. Reference to Fig. III.B-2 shows t_v can be reduced from 0.042 m to 0.006 m. The vacuum tank thus contributes a small amount to the TFC stiffness, and its mass can be much reduced, $m_{VT}^{TF} = 135 \text{ Mg}$.

The STARFIRE shear panels were sized to limit the out-of-plane tilting of the TF coils. The deflection, d , is linear with the out-of-plane force P_1 :

$$d = \frac{hF P_1}{Gwt_{sp}}, \quad (\text{III.B-2})$$

where h , w , and t_{sp} are the panel height, width, and thickness, G is the modulus of rigidity, and F is a safety factor. The dimensions in STARFIRE resulted in a total panel mass of $m_{sp} = 838 \text{ Mg}$. Since P_1 is reduced by $\sqrt{1.5}$ for STAR-B the thickness, t_{sp} , and mass are proportionally reduced. At \$24/kg the 20% reduction in steel results in ~ \$4 M savings for this inter-coil support structure.

Figure III.B-2. The required thickness of the vacuum tank structure (t_v) as a function of polarization due to the reduced out-of-plane forces.

The reduction of I_0 in STAR-B will of course reduce the cost of the EFC system. Since the EFC field is reduced by $(1.5)^{1/4}$ its stored energy, U^{EF} is reduced by about $\sqrt{1.5}$. Whereas the $U^{EF} = 10$ GJ for STARFIRE, it is reduced to $U^{EF} \approx 8.2$ GJ for STAR-B. The price of the EFC for STARFIRE is \$30.5 M, and for STAR-B, the cost in Table III.B-3 is simply scaled by the reduction in EFC stored energy.

The benefits to noninductive current drive may be substantial if polarized fuels are realized. For STAR-B we have reduced I_0 by $(1.5)^{1/4}$, but also the average electron density, $\bar{n}_e$, is reduced. Since $\beta \sim \bar{n}_e \bar{T}_i / B_0^2$ we find $\bar{n}_e$ is reduced by $\sqrt{1.5}$ when $\bar{T}_i$ is held constant for STAR-B. Current driver power⁽⁶⁾ is proportional to $\bar{n}_e I_0$, so it is reduced by $(1.5)^{3/4} = 1.36$ in STAR-B. Table III.B-2 shows the rf plasma heating by the lower hybrid wave driver for STARFIRE, $P_h^{CD} = 90.4$ MW, and the electric power required for the system, $P_e^{CD} = P_h^{CD} / (0.592) = 152.7$ MW. This resulted in net electric output from the power plant of $P_{net} = 1200$ MW. For STAR-B, P_e^{CD} is reduced and the plant output increases to $P_{net} = 1240$ MW. (The power balance benefits even more if the electric-to-rf efficiency, η_d , is somewhat lower. For example,⁽⁴⁾ if $\eta_d = 0.25$ we would have $P_{net} = 991$ MW for STARFIRE and $P_{net} = 1086$ MW for STAR-B, representing $\sim 10\%$ increase in output power.) However, the capital cost reductions do not scale as strongly as $(1.5)^{3/4}$. The reason is that, according to dynamic simulations of start-up, a minimum power ≈ 75 MW is needed to ignite the plasma. Although $P_h^{CD} = 66.6$ MW for STAR-B, if the auxiliary heating and current drive systems are the same, the realized capital cost reductions from the STARFIRE design are only proportional to $(90.4 \text{ MW} - 75 \text{ MW}) = 15.4$ MW. The cost savings in Table III.B-3 assume the rf system can be assembled for \$1/W. Naturally, if the current drive system were more expensive,⁽⁴⁾ e.g., \$2-4 per watt, the capital savings would be considerably higher.

The reductions in capital costs achieved by STAR-B may be viewed in perspective to the total power plant direct capital cost. The balance of the reactor plant costs (those insensitive to fuel polarization) are included in Table III.B-3. The savings, \$56.5 M, for STAR-B represent a $\sim 2.5\%$ reduction from the STARFIRE total direct capital cost. Apparently STARFIRE would be more attractive if polarized fuels could be employed at a cost somewhat less than this \$56 M.

Additional benefits may accrue from the use of polarized fuels in terms of lessening the damage associated with plasma disruptions. The plasma kinetic energy content is reduced for STAR-B by $\sqrt{1.5}$ since it is proportional to $\sim \bar{n}_e \bar{T}_i$. Likewise the poloidal field energy is reduced for STAR-B by $\sqrt{1.5}$, as it is proportional to $L_0 I_0^2$, where L_0 is the toroidal self inductance. This reduction in plasma free energy (U_{free}) by $\sqrt{1.5}$ may lessen the effects of the worse case disruptions. Figure III.B-3 shows that for the worst case disruptions on the STARFIRE limiter's front face (2500 J/cm^2) roughly $270 \mu\text{m}$ of W surface could be vaporized and melted by a long duration (100 ms) plasma dump. However, the damage is very nonlinear with energy deposition. If the energy content is reduced by $\sqrt{1.5}$ to $\sim 2040 \text{ J/cm}^2$, then only $\sim 50 \mu\text{m}$ of surface material could be lost. On the first wall the worst case (800 J/cm^2) might remove $300 \mu\text{m}$ of V; this could be reduced to $\sim 150 \mu\text{m}$ with the reduced energy of the STAR-B reactor plasma. More importantly, there are thresholds for damage, shown in the figure, and modest reductions in plasma energy might essentially remove this particular damage mechanism. (Shorter disruption times move the thresholds to lower energy, and crack initiation and propagation may occur in any event. So it is not likely that disruption damage will completely vanish as a concern.)

III.B.1.2 Benefits to Lower Beta - STAR-B

The achievable plasma beta in a fusion reactor is of course a significant uncertainty at present. The STARFIRE value, $\beta = 0.067$, was found stable to almost all virulent ideal MHD modes studied.⁽⁷⁾ Hollow current density equilibria were also examined for JET⁽⁸⁾ and were found stable at $\beta \gtrsim 0.10$. These results indicate a scaling $\beta \simeq 0.24/A$ if $\kappa \simeq 1.65$ and the current density/safety factor can be optimized. However, other tokamak stability studies, using less optimized current density profiles, have less optimistic predictions of stability scaling:

$$\text{Sykes}^{(9)} \quad \beta = 0.035 \mu_0 I_0 / a B_0, \quad (\text{III.B-3})$$

$$\text{Bernard}^{(10)} \quad \beta = 0.27 A^{-1.3} \kappa^{1.2} q_b^{-1.1} (1 + 1.5 \delta), \quad (\text{III.B-4})$$

where δ is a measure of the plasma cross sectional triangularity. According to these latter scaling laws the beta in STARFIRE would be considerably

Figure III.B-3. Material erosion as a function of energy deposition for 316 SS, V, Be, and W.

smaller than 0.067. It is interesting then to see how polarized fuels might permit operation of STARFIRE at lower beta.

By Eq. (1) we note the factor 1.5 increase in σ only reduces β by the factor $\sqrt{1.5}$. So in Table III.B-2 we include a reactor version, called STAR-B, which operates with $\beta = 0.0547$ and the same fusion power, wall load, and maximum field as for STARFIRE. The main benefit is that the density is also reduced $\sqrt{1.5}$ if $\bar{T}_1$ is held constant. However, since the equilibrium current, I_0 , is insensitive to beta and proportional to B_0 , the value of I_0 and the size of the EFC system do not change. Thus, the main capital cost reduction relative to STARFIRE is in the current drive system, since $P_h^{CD} \propto I_0 n_e$. As with STAR-B, though, at least 75 MW of heating needs to be installed for startup. The circulating electric power, P_e^{CD} , for steady state current drive (RFCD) is less than for STARFIRE but more than for STAR-B. Reference to Tables III.B-2 and III.B-3 shows STAR-B is only \$15 M cheaper than STARFIRE and produces only 28 MW additional net power; it does not need as high a beta, however.

Finally, we note there is lower plasma thermal energy which can be released by a major disruption. However, the inductive energy, $\sim L I_0^2$, is unchanged from STARFIRE. Thus, the potential disruption damage is lower than for STARFIRE but not as small as STAR-B might suffer.

III.B.1.3 Benefits of Higher Temperature - STAR-T

Selection of the operating temperature is a critical decision for the current drive (RFCD) in a tokamak reactor. At fixed beta the density decreases as $\bar{T}_e$ increases, and this benefits RFCD. However, the fusion reactivity also drops as $\bar{T}_i$ increases above 10-15 keV, so reactor performance may suffer too much to opt for high temperature RFCD.

Figure III.B-4 shows this tradeoff for STARFIRE with $B_m = 11.1$ T and $\beta = 0.067$. In fact, P_h^{CD} is reduced by 36% if $\bar{T}$ is raised from ~ 19 keV to 24.5 keV, corresponding to a decrease in P_f and W_n by a factor 1.5. Assuming polarized fuels could restore P_f to the STARFIRE level, then such a reactor, denoted STAR-T in Table III.B-2, would benefit by operating at low $\bar{n}_e$ ($7.5 \times 10^{19} \text{ m}^{-3}$). The power balance is more attractive, $P_{net} = 1256$ MW, although the minimum capital expense, corresponding to $P_h^{CD} = 75$ MW, would still be required.

Figure III.B-4. Fusion power (P_f), lower hybrid current drive power (P_{LH}), net electric power (P_n), $Q (\equiv P_f/P_{LH})$, neutron wall load (W), and capital cost of electricity (C) at various operating temperatures; $R = 7.0$ m, $B_0 = 5.8$ T, $\beta_t = 0.067$, $A = 3.6$, $\kappa = 1.6$, $d = 0.5$, $\alpha = 1.4$, $\alpha_n = 1.1$, $\Delta = 1.4$ m, and equal ion and electron confinement times ($T_i \sim T_e$).

With respect to disruptions, we note that STAR-T has the same free energy as STARFIRE, since the kinetic energy, proportional to βB_0^2 , and the inductive energy, $\sim L I_0^2$, are unchanged from the STARFIRE values. Thus, disruption damage is not mitigated by going to this alternative.

III.B.2 Tokamak in the Second Stability Regime

As suggested above, a judicious choice of the safety factor (or current density) profile can permit theoretical ideal MHD stability at beta above the values given in Eqs. (III.B-3) and (III.B-4). Figure III.B-5 shows schematically a smaller reactor ($R_0 = 5.25$ m) than STARFIRE with an elongated, nearly elliptical plasma. Figure III.B-6 displays the profiles of the safety factor (Q), diamagnetism (G), and plasma pressure (P) with $\sqrt{\psi}$ as the abscissa, where ψ is the poloidal flux. The toroidal current density (J) is shown with the major radius as the abscissa. Note that J is peaked toward the outboard edge and reversed inboard. The safety factor varies from $q_a = 1.10$ on axis to $q_b = 5.05$ at the limiter and is linear in ψ ; and the total toroidal current is quite low, $I_0 = 4.32$ MA, for a vacuum value of the diamagnetic function $F_0 \equiv R_0 B_0 = 19.58$ T-m. For this equilibrium the Sykes scaling, Eq. (III.B-3), would predict a maximum stable $\beta = 0.058$, and Bernard's prediction, Eq. (III.B-4), would be $\beta = 0.014$. However, calculations have shown this equilibrium is stable to all ideal modes, provided a conducting first wall is near the plasma surface, at values in excess of $\beta = 0.20$. In theory, then, there is ample reason to suspect that much higher β is achievable than assumed by the STARFIRE study. A reference tokamak reactor (with $\beta = 0.25$) is given in Table III.B-4. In Table III.B-5 the features of several alternatives operating with polarized fuels at these higher betas are given.

We will explore the benefits of polarized fuels by studying the changes from the reference case for various modifications. Table III.B-6 attempts to quantify these benefits in terms of changes in the direct capital costs of the modified reactors. Inasmuch as the reference case has not been costed in detail, approximate scaling laws have been used. Both the TFC and EFC magnets are costed linearly in stored energy, normalized to the STARFIRE values. (These cost estimates appear very low compared to the FED/INTOR values,⁽¹¹⁾ but our costs assume the groundrules promulgated in Ref. (3), i.e., tenth of a kind reactor with several decades of experience and learning curves.) As

Figure III.B-5. Cross-section of the TF coils for a small reactor ($R_0 = 5.25$ m) with an elongated, nearly elliptical plasma.

Figure III.B-6. Profiles of the safety factor, the toroidal current density, diamagnetism, and plasma pressure.

Table III.B-4. Common Reactor Parameters for a High Beta Reactor and Several Alternatives Which Use Polarized Fuels

Parameter	Unit	Ref/(Several Alternatives)
A		6.0
κ		2.0
α_n		0.3
α_T		1.1
$\Delta_{B/S/V}^i$	m	1.04

above we choose \$1/W to represent RFCD system costs, and we assume at least 75 MW is required (for auxiliary heating). The electric efficiency for RFCD is taken to be $\eta_d = 0.55$. The balance of plant (BOP) has an economy of scale which we take as cost, $BOP \propto (P_f)^{0.7}$, normalized to STARFIRE. The various reactors in Table III.B-5 differ additionally from the STARFIRE series by the following characteristics: smaller size ($R_o < 7.0$ m), less net power ($P_{net} < 1200$ MW), and higher thermal efficiency ($\eta_{th} = 0.45$).

III.B.2.1 Benefits of Lower Toroidal Field - MOD-B

Assuming again that the increase of $\sigma = 1.5 \sigma_o$ is possible with polarized fuels, than with the wall load and fusion power held invariant, advantage may be taken by using a smaller toroidal field than for the reference reactor. Table III.B-5 indicates $B_M = 5.42$ T instead of 6.00 T. Also, I_o is slightly reduced, to ~ 3.6 MA. The TFC and EFC are accordingly less expensive, as shown in Table III.B-6, however the savings are small ($\sim \$3.5$ M) since in the second stability regime the magnet systems are already reduced significantly from the STARFIRE design. An additional \$5 M savings derives from the rf current drive system since $\bar{n}_e$ and I_o are reduced from the reference. The net electric power also improves due to the much smaller circulating power, $P_e^{CD} = 107$ MW. Consequently the (direct) cost of power is more attractive than for the reference. Note, however, the cost of supplying polarized fuels is not

Table III.B-5. Variable Reactor Parameters for a High Beta Reactor and Several Alternatives Which Use Polarized Fuels

Parameter	Unit	Ref.	MOD-B	MOD- β	MOD-T	MOD-W	MOD-R
σ	σ_m	1.0	1.5	1.5	1.5	1.5	1.5
R_o		5.25	5.25	5.25	5.25	5.25	4.59
$\overline{T}_i$	keV	25.9	25.9	25.9	~39	25.9	25.9
β		0.25	0.25	0.20	0.25	0.25	0.25
B_o	T	3.83	3.46	3.83	3.83	3.83	3.83
I_o	MA	3.99	3.61	3.99	3.99	3.99	3.49
P_f	MW	1275	1275	1275	1275	1912	1275
W_n	MW/m ²	3.40	3.40	3.40	3.40	5.10	4.46
P_h^{CD}	MW	80	59	65	53	80	61
P_e^{CD}	MW	145	107	119	97	145	111
L^{TFC}	m	18.6	18.6	18.6	18.6	18.6	17.2
B_M	T	6.00	5.42	6.00	6.00	6.00	6.43
R_1	m	3.10	3.10	3.10	3.10	3.10	2.52
R_2	m	8.10	8.10	8.10	8.10	8.10	7.08
H_{max}	m	3.22	3.22	3.22	3.22	3.22	3.02
$N^{TFC} I^{TFC}$	MA	100	90	100	100	100	100
U^{TFC}	GJ	5.0	4.1	5.0	5.0	5.0	3.0
Δ_{TFC}	m	0.50	0.45	0.50	0.50	0.50	0.53
$\overline{n}_e$	10 ²⁰ m ⁻³	1.77	1.45	1.45	1.18	1.77	1.77
P_{net}	MW	540	578	555	588	865	574
U^{EF}	GJ	0.3	0.2	0.3	0.3	0.3	0.2

included in Table III.B-6. If this additional cost would exceed \$5 - 10 M then there is evidently no capital cost benefit to be realized.

III.B.2.2 Benefits to Lower Beta - MOD- β

By retaining $B_m = 6.0$ T and the reference wall load and P_f , the adoption of polarized fuels would permit operation at $\beta = 0.20$. In addition to being more conservative in terms of physics goals, this reduces RFCD power, since $\bar{n}_e$ is lowered from the reference. The TFC and EFC are identical with the reference case.

III.B.2.3 Benefits of Higher Temperature - MOD-T

In the high temperature region $\langle \sigma v \rangle / T^2 \sim T^{-1}$, so if $\bar{T}_i$ is increased by a factor 1.5 then P_f and W_n are unchanged if $\sigma \rightarrow 1.5 \sigma_0$. This reactor, denoted MOD-T in Table III.B-5, is characterized by the low electron density and is very favorable to RFCD. The benefits of smaller circulating power is reflected in the cost of power shown in Table III.B-6.

This particular reactor also has the least extrapolation of density above the empirical Murakami limit. The parameter $\bar{n}_e R_0 / B_0$ has reached $7.7 \times 10^{19} \text{ m}^{-2} \text{ T}^{-1}$ in the FT experiment (Frascati tokamak), whereas INTOR studies have suggested values as high as $13.2 \times 10^{19} \text{ m}^{-2} \text{ T}^{-1}$. MOD-T has a value of $16.2 \times 10^{19} \text{ m}^{-2} \text{ T}^{-1}$, whereas the Reference reactor is even further beyond current experience at $24.3 \times 10^{19} \text{ m}^{-2} \text{ T}^{-1}$. It may well be that the boundaries of the Hugill diagram are not relevant to tokamaks with RFCD in the second stability regime. In the past the operational boundaries on density have expanded with the introduction of new techniques such as gettering and gas puffing. So it is too early to assess whether the relatively low $\bar{n}_e$ of MOD-T is in practice an operational advantage compared to the alternative reactors.

III.B.2.4 Benefits of Higher Wall Load - MOD-W

We consider the possibility of setting $\sigma = 1.5 \sigma_0$ without any other changes from the reference reactor. In such a case the fusion power and wall load both increase by 1.5, although P_h^{CD} is unchanged. As shown in Tables III.B-5 and III.B-6 this reactor, MOD-W, has a much higher net electric power production; the balance of plant dominates the capital costs for reactors in the second stability regime so the capital cost increases roughly as

Table III.B-6. Comparison of Capital Costs for a High Beta Reactor and Several Alternatives Which Use Polarized Fuels

Parameter	Unit	Reference	MOD-B	MOD-β	MOD-T	MOD-W	MOD-R
TFC cost	\$M	18.6	15.3	18.6	18.6	18.6	14.9
EFC cost	\$M	0.9	0.7	0.9	0.9	0.9	0.7
RFCD cost in excess of 75 MW	\$M	<u>5.0</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>	<u>5.0</u>	<u>0.0</u>
Cost, polar ^a	\$M	24.5	16.0	19.5	19.5	24.5	15.6
Cost, BOP ^b	\$M	<u>905.8</u>	<u>905.8</u>	<u>905.8</u>	<u>905.8</u>	<u>1202.9</u>	<u>905.8</u>
Cost, total	\$M	930.3	921.8	925.3	925.3	1227.4	921.4
Direct cost of power ^c	\$/W	1.72	1.59	1.67	1.57	1.42 ^d	1.61

^a Polar: Reduction in magnet and current driver capital costs associated with the use of polarized fuel. The cost of producing polarized fuels is not included.

^b BOP: Balance of plant.

^c The cost of producing polarized fuels is not included.

^d If increased maintenance on the inner first wall is required, then the \$/W may equal that of the reference \$1.72/watt.

$(1.5)^{0.7}$. The decrease in the cost of power is attributed mainly to economies of scale, not to the benefits of increased reactivity.

The larger neutron wall load, W_n , is of concern for MOD-W. In addition, the parallel DT polarization results in a $\sin^2\theta$ neutron birth distribution⁽¹⁾ which weighs the virgin neutron wall load towards the inboard region.^(1,2) Hence, the local uncollided wall load in the inboard region is increased by more than a factor 1.5, and we might expect this would significantly reduce the time between first wall/blanket replacements. Thus, although MOD-W offers lower capital cost, its availability is lower than for the reference reactor, so the cost of energy may not be less than for the reference case.

III.B.2.5 Benefits of Smaller Size - MOD-R

A possible design alternative might be to design a more compact reactor to capitalize on the higher power density of polarized fields for a given B_0 and plasma temperature. In Table III.B-5 we include one option, MOD-R, which has a power density 1.5 times higher but with the same fusion power as the reference reactor. The major and minor radii are reduced slightly, by $(1.5)^{1/3}$ from the reference, and the first wall area is reduced by $(1.5)^{2/3}$; consequently the neutron wall load is higher than for the reference, which may lower its availability. Also, for fixed B_0 and $\Delta_{B/S/V}^i$, the maximum field, B_m , must increase significantly, to ~ 6.4 T. Cost savings may be expected with the smaller TFC. R_1 is reduced since the major radius is smaller, and R_2 , set by the ripple criterion, is also smaller. The stored energy, U^{TFC} , is roughly 80% of the reference case, and this is shown in Table III.B-6 as a cost savings.

The value of I_0 is proportional to R_0 for fixed B_0 , A , κ , and β , so I_0 is reduced by $(1.5)^{1/3}$, and U^{EF} is reduced by $(1.5)^{2/3}$. In addition to reducing the EFC cost, we note that the RFCD system is cheaper. $P_h^{CD} \propto R_0 I_0$, so P_h^{CD} is reduced by $(1.5)^{3/4}$.

Besides having a lower capital cost, the circulating power is reduced for this device. However, reference to Table III.B-6 shows that MOD-R does not promise large economic changes relative to the other options. In fact, the smaller I_0 and minor radius may jeopardize the confinement properties of this device. This concern is partially offset by the reduced requirement for $n\tau$ (roughly 1.5 lower at $\bar{T}_i \approx 30$ keV) with polarized fuels.⁽¹²⁾

III.B.3 Conclusions

This section has focused on plasma engineering in examining the benefits of polarized fuel. The general scenarios considered for the reactor with higher beta can be summarized under two classifications: constant wall loading or increased wall loading. For the scenarios in which constant wall loading was assumed, two cases resulted: 1) one in which only the current driver requirements were reduced, and 2) one in which both the magnetic field and the current drive requirements were reduced. The latter resulted in the greater capital cost reduction. When an increased wall loading was allowed, two other cases resulted: 1) one in which increased fusion power was produced with the same size reactor, and 2) one in which a slightly smaller reactor was feasible for the original fusion power. The smaller reactor had a capital cost reduction comparable to the best case in the constant wall loading case. The reactor with increased power can be compared with the other polarized fuel alternatives only by examining the direct cost of electricity. Under this criterion, the increased power reactor is superior. However, operating costs may be significantly higher for the increased power reactor. A more detailed study would be required to evaluate overall operating costs.

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III.C Effects of Polarized DT Plasmas on Nuclear Design of Fusion Reactors

III.C.1 Calculational Model

In order to assess the effects of polarized DT plasmas on the nuclear design aspects of fusion reactors, three plasma cases are considered. The first case has no polarization of the reactants (D and T) where the angular distribution of reaction products is isotropic. In the second case, the deuterons are polarized perpendicular to the direction of the magnetic field and the tritons have no polarization. This case gives the same fusion reactivity as the first case except the angular distribution of reaction products⁽¹⁻³⁾ is proportional to $(1 + 3 \cos^2 \theta)/8 \pi$. In this distribution, θ is the polar angle measured with respect to the magnetic field direction. This distribution produces a peak value for the DT neutrons in the direction of the magnetic field. The third case has both the deuterons and tritons polarized along the magnetic field direction which produces a 50% increase in fusion reactivity. The plasma engineering aspects of this case were considered in Section III.B. The corresponding angular distribution of reaction products is proportional to $3 \sin^2 \theta/8 \pi$, which causes more DT neutrons to travel perpendicular to the magnetic field direction. Table III.C-1 gives a summary of the main characteristics of these three cases.

Table III.C-1. Main Characteristics of DT Plasmas with Different Polarization

Case No.	Plasma Polarization	Neutron Angular Distribution $F(\theta)$	Reactivity Change Relative to the First Case
1	None	Isotropic	--
2	D polarized perpendicular to magnetic field, T none	$\frac{1 + 3 \cos^2 \theta}{8 \pi}$	None
3	D and T polarized along magnetic field	$\frac{3 \sin^2 \theta}{8 \pi}$	+ 50%

A three-dimensional geometrical model describing a tokamak reactor was developed for the analysis. The reactor has a major radius (R_0) of 5.25 m, plasma radius (a_0) of 0.875 m, and plasma elongation (κ) of 2. The scrapeoff layer thickness is 0.08 m at the midplane. The plasma boundary is fitted to a D-shape defined as follows:

$$\begin{aligned} R &= R_0 + a_0 \cos(t + 0.25 \sin t) \\ Z &= a_0 \kappa \sin t \end{aligned} \quad (\text{III.C-1})$$

where (R, Z) describes a point on the plasma boundary and t is a parameter which varies from 0 to 2π . A uniform spatial source distribution was used to clearly identify the effect of the plasma polarization. The neutron source distribution $N(E, \theta)$ is described as follows:

$$N(E, \theta) = F(\theta) \cdot n(E) \quad (\text{III.C-2})$$

where $F(\theta)$ is the angular distribution as defined in Table III.C-1 for the three cases, and $n(E)$ is the neutron energy spectrum.

$$n(E) = C \exp - \left(\frac{\sqrt{E} - \sqrt{B}}{A} \right)^2, \quad (\text{III.C-3})$$

where $C = 1.68$, $B = 14.07$ MeV, and $A = 0.56$ MeV.

The blanket in this model has liquid lithium for tritium breeding and heat removal, a vanadium structure, and a steel reflector. The hot shield concept was employed where the shield is integrated with the blanket and cooled with the same coolant. Table III.C-2 gives the material compositions and zone thicknesses used for the analysis. This concept was developed as part of ANL's Tokamak Power Systems Study in FY 1985.

The neutron and neutron-induced photon transport calculations were performed with the MCNP code,⁽⁴⁾ which is a general Monte Carlo code for neutron and photon transport. A source routine was developed and integrated with MCNP to sample the different angular distributions of the DT neutrons. Continuous energy representation for nuclear cross sections (pointwise data) was used for the transport calculations. All the nuclear cross sections were generated from ENDF/B-V data files. Two variance reduction schemes were employed to

Table III.C-2. Blanket and Shield Parameters^a

Zone Description	Zone Thickness (cm)	Zone Composition (Vol. %)
First Wall	1	50% V15Cr5Ti, 50% Li ^b
Breeding	23	7.5% V15Cr5Ti, 92.5% Li ^b
Reflector	36	10% V15Cr5Ti, 10% Li ^b , 80% type Fe1422 steel
Shield	46	10% V15Cr5Ti, 10% Li ^b 80% type Fe1422 steel
Gap	2	100% vacuum
Dewar	5	100% Nitronic-33 steel
Gap	2	10% insulator
Coil case	5	100% Nitronic-33 steel
Superconductor	5	35% Nitronic-33 steel, 15% insulator, 31.5% copper, 3.6% NbTi, 15% liquid He

^a Outboard and inboard sections are the same.

^b Natural lithium.

improve the efficiency of the calculations: these are zone splitting and weight cutoff with Russian roulette. Neutron fluxes and nuclear heating rates without decay energy were calculated in all zones as well as the uncollided current and flux at the first wall.

Figure III.C-1 shows the geometrical model used in the calculations where a reflective boundary condition was assumed at the midplane. The toroidal field (TF) coils were assumed to cover the whole outer shield surface in this model. This assumption causes an increase in the total nuclear heating of the TF coils. This increase is approximately proportional to the increase in the surface area between the TF coils and the shield.

Figure III.C-1. Geometrical model for the calculations.

III.C.2 Results

The effect of plasma polarization on the uncollided neutron current at the first wall surface is shown in Fig. III.C-2. The neutron current was calculated at intervals of 5 degrees each in the poloidal direction with a statistical error of less than 1%. In each interval, an average value is used to plot the results. The valleys in Fig. III.C-2 are caused by the corners in the first wall model at 62, 88.5, and 142 degrees. The isotropic case (case 1) shows the maximum value of the uncollided current at 180 degrees. The difference between the maximum and the minimum value is $\sim 20\%$. The minimum value is at 0 degrees, ignoring the valleys due to the corners in the first wall model.

The second case, where the neutron distribution is peaked in the direction of the magnetic field, tends to increase the current at the outboard section of the first wall and reduce the current at the inboard section. The third case which enhances the fusion reactivity shows an effect opposite to that for the second case for the same neutron wall loading (i.e. source strength). At the midplane, the two polarized cases produce about an 18% change in the uncollided current relative to the unpolarized case (case 1). The changes are of opposite sign as shown in Fig. III.C-2. It should be noted that this change in the uncollided current does not produce an 18% change in the nuclear responses (i.e. nuclear heating, total neutron fluence, etc.). In fact, the uncollided neutron current and flux do not correlate to any design quantity. For a first wall design, nuclear heating is the key parameter for thermal hydraulics; radiation damage is proportional to the neutron fluence. However, the uncollided profiles reflect the changes in the neutron source characteristics from the different plasmas.

The uncollided neutron fluxes for the three cases are shown in Fig. III.C-3 where a behavior similar to that in Fig. III.C-2 is observed. However, the changes at the inboard section of the first wall are less than 6% relative to the isotropic case. At the outboard section the effect was about 34%.

The fast ($E > 0.1$ MeV) and the total ($E > 0.0$ MeV) neutron fluxes in the first wall are plotted in Figs. III.C-4 and III.C-5. They are very similar to the uncollided flux shown in Fig. III.C-3. The fast fluence for the second case shows a strong deviation from that for the first case which produces a

Figure III.C-2. Spatial distributions of uncollided neutron current at the first wall surface for DT neutron source with different angular distributions.

Figure III.C-3. Spatial distributions of uncollided neutron flux at the first wall surface for DT neutron source with different angular distributions.

Figure III.C-4. Spatial distributions of fast neutron flux in the first wall ($E > 0.1$ MeV) for DT neutron source with different angular distributions.

Figure III.C-5. Spatial distributions of total neutron flux in the first wall ($E > 0.0$ MeV) for DT neutron source with different angular distributions.

20% increase in the replacement rate of the outboard first wall. This means that the DT neutron shift to the outboard (case 2) is not desirable due to increased first wall maintenance requirements. On the other hand, the third case which shifts the DT neutron flux perpendicular to the magnetic field reduces the frequency of the first wall replacement by ~ 5%.

Figure III.C-6 shows the nuclear heating profile in the first wall for the same three cases. For the second case the maximum nuclear heating in the first wall is increased by ~ 20% and the total nuclear heating by ~ 8%. These increases are not desirable from a heat transfer design point of view. The third case shows an opposite effect, a decrease in nuclear heating, because the angular distribution reduces the average travelling distance of the neutrons in the first wall. Table III.C-3 shows the nuclear heating in the different reactor zones per fusion neutron. Table III.C-4 gives the percentage changes in nuclear heating relative to the unpolarized case. Polarization of the plasma reduces the total energy deposition in the blanket and shield by < 1% for both Cases 2 and 3. However, the energy deposition in the TF coils increases by 7.5% and 13.5% for cases 2 and 3, versus that for the unpolarized case.

Table III.C-5 gives the tritium breeding ratio for the three cases. Case 2 increases the TBR by about 2% relative to the unpolarized case. This increase results from directing the DT neutrons to the outboard blanket where the breeder volume is larger relative to the inboard section. Case 3 increases the inboard tritium breeding by ~ 10% and reduces the outboard breeding by ~ 5% resulting in a net decrease of 1%.

The nuclear responses in the TF coils are shown in Table III.C-6. In case 2 the fast neutron fluence in the inboard section of the TF coils is reduced by ~ 10% relative to the unpolarized case. The outboard neutron fluence is about the same. However, the nuclear heating in the outboard section is increased by about 38% at the midplane which requires an additional 3 cm of shielding. Case 3 produces the opposite effects as were found for case 2 with respect to the inboard section. On the outboard section, the same size shield is required for the same neutron wall load at the first wall. However, for the 50% increase in the neutron wall loading, a 6 cm increase in the inboard shield thickness is needed.

Figure III.C-6. Spatial distributions of nuclear heating in the first wall for DT neutron source with different angular distributions. normalized to 1 MW/m² neutron wall loading.

Table III.C-3. Energy Deposition Per Fusion Neutron (MeV)

Zone	Case		
	1	2	3
First wall	0.66	0.71	0.61
Breeding zone	9.55	9.75	9.32
Reflector	7.03	6.75	7.16
Shield	0.89	0.87	0.92
Total	18.13	18.08	18.01

Table III.C-4. Percent Change in Energy Deposition Relative to the Unpolarized Case

Zone	Case	
	2	3
First wall	+ 7.5	- 7.6
Breeding zone	+ 2.1	- 2.4
Reflector	- 4.0	+ 1.8
Shield	- 2.2	+ 3.4
TF coils	+ 7.5	+13.5
Total	- 0.3	- 0.7

Table III.C-5. Tritium Breeding Ratio for Three Cases -
1: Unpolarized; 2 and 3: Polarized

Zone	Case		
	1	2	3
Inboard	0.324	0.311	0.357
Outboard	0.845	0.882	0.802
Total	1.170	1.193	1.159

Table III.C-6. Nuclear Responses in the TF Coils at the Midplane Normalized
to 1.0 MW/m² Neutron Wall Loading or 1.0 MW·y/m² of Operation

Parameter	Case		
	1	2	3
Insulator dose, rads			
Inboard	2.6×10^{10}	2.7×10^{10}	4.0×10^{10}
Outboard	2.6×10^{10}	3.2×10^{10}	2.3×10^{10}
Nuclear heating in the winding materials, mW/cm ³			
Inboard	18	19	25
Outboard	16	22	17
Fast neutron fluence in the winding materials (E > 0.1 MeV) n/cm ²			
Inboard	5.4×10^{18}	4.9×10^{18}	5.8×10^{18}
Outboard	4.9×10^{18}	5.0×10^{18}	4.3×10^{18}

III.C.3 Summary

For case 2 in which the DT neutrons are peaked in the magnetic field direction, the frequency of the first wall replacement increases by 20%. The inboard shield thickness is unchanged relative to the isotropic (unpolarized) case, but the outboard shield is increased by 3 cm to achieve the same nuclear responses in the TF coils.

For case 3 the first wall life is increased by 5% but about 3 cm additional shield thickness is required for the inboard section. The total nuclear heating in the first wall is also reduced by ~ 8%. In addition, the spatial distribution of the various nuclear responses is smoothed.

The impact on the total tritium breeding ratio is less than 2% for either of the polarized cases relative to the isotropic (unpolarized) case.

References for Section III.C

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2. B. J. Micklich and D. L. Jassby, "Implications of Polarized DT Plasmas for Toroidal Fusion Reactors," PPPL-1994, Princeton Plasma Physics Laboratory (1983).
3. H. Takahashi and O. W. Lazareth, "Effect of Polarized Fusion on the Neutronics of a Mirror Fusion Reactor," Trans. Am. Nucl. Soc. 44, 149 (1983).
4. Los Alamos Monte Carlo Group, "MCNP - A General Monte Carlo Code for Neutron and Photon Transport, Version 2B," LA-7936-M, Revised, Los Alamos National Laboratory (1981).

IV. SYSTEM IMPLICATIONS

This section examines some of the effects that the use of polarized fuels has on other reactor systems. The three systems/issues addressed are radio-frequency systems, impurity control, and material requirements in the plasma chamber.

IV.A Radiofrequency Systems

The main concern with rf heating or rf current drive (RFCD) is that electromagnetic waves of angular frequency $\omega \sim 0[\Omega_D]$, where Ω_D is the deuteron cyclotron angular frequency, may depolarize the plasma.⁽¹⁾ On this basis we note that the STARFIRE reactor could accommodate polarized fuels, since the lower hybrid wave employed for heating and RFCD has $\omega/2\pi = 1.7 \text{ GHz} \gg \Omega_D/2\pi = 88 \text{ MHz}$.

However, if a low frequency fast wave were employed the situation would change. Unfortunately, for polarized fuels, waves with $\omega \sim 0[\Omega_D]$ are very attractive for heating and RFCD. Calculations for JET⁽²⁾ detail the benefits of ICRH, especially fundamental minority deuterium heating, for creating non-maxwellian tails and enhancing the DT reactivity in present-day large tokamaks. In Ref. (2) it is shown that reactivity is enhanced by a factor of two by generating nonmaxwellian deuterium distributions with ICRH. Thus it makes more sense to employ ICRH with unpolarized fuel for the TFTR/JET class of devices.

Calculations of RFCD have also identified the ICRF region as very attractive. Both the DEMO study⁽³⁾ and the FED-A study⁽⁴⁾ suggested that the best RFCD candidate is the fast wave near the second deuterium cyclotron harmonic. Figure IV.A-1 shows the location of cold ion resonances for an advanced tokamak reactor (typical of the second stability regime, as envisioned in the TPSS work by ANL) with a large aspect ratio ($A = 6.0$), $B_0 = 3.62 \text{ T}$, RFCD at 42.1 MHz, and assuming the only ions are D, T, Be, and He. This particular frequency is chosen to enhance RF wave penetration towards the magnetic axis (fast wave polarization), to avoid cold ion parasitic resonance damping, and to maximize electron (Landau and transit-time) damping relative to hot alpha damping. There is a clear danger of destroying fuel polarization if such an RFCD technique were employed. The advantages of steady state operation are myriad,⁽⁵⁾ and it is thus problematic whether it is desirable to

Figure IV.A-1. Location of cold ion resonances for an advanced tokamak reactor.

forsake these benefits from such a promising driver in order to achieve the reactivity enhancement of polarization.

Finally, another advantage of polarized fuels may lie in potential reductions in auxiliary heating power required to ignite the plasma. Increased reactivity introduces more alpha heating late in the start up phase, which reduces the RF power required. Analysis of FED, a small reactor⁽⁶⁾ with $R_0 = 5.0$ m and capable of $P_f \gtrsim 1000$ MW, showed the minimum auxiliary heating power, P_h , would be ~ 30 MW, and at that point about 20 MW of alpha heating, P_α , occurs. Hence, enhancing P_α by 1.5 would permit P_h to be reduced to ~ 20 MW. However, the minimum value of P_h would require very long start up times. In practice, larger P_h is chosen to ignite in a reasonably short time; $P_h = 50$ MW was chosen for FED. We might expect, therefore, for a commercial reactor that P_h could be reduced somewhat if polarized fuels are used as an aid to ignition. As an example, STARFIRE, which required 75 MW of auxiliary heating, might need ~ 25 MW less heating. At \$1/W this would translate into a \$25 M savings of direct capital cost. We must keep in mind that this savings is eliminated if the auxiliary heating depolarizes the plasma (e.g., as with ICRH).

References for Section IV.A

- (1) R. M. Kulsrud, E. J. Valeo, and S. Cowley, PPPL-2099 (1984).
- (2) J. Scharer, et al., Nucl. Fusion 25 (1985) 435.
- (3) DEMO-Interim Report ANL/FPP/TM-154 (1982).
- (4) Y-K. M. Peng, P. H. Rutherford, et al., ORNL/FEDC-83/1 (1983).
- (5) D. A. Ehst, et al., "Nucl. Eng. and Design/Fusion 2 (1985) 305; D. A. Ehst, et al., ibid., p. 319.
- (6) C. A. Flanagan, D. Steiner, G. Smith, et al., ORNL/TM-7948/V1 (1981).

IV.B Impurity Control Issues in a Reactor With Polarized Fuel

The key issue for impurity control in a tokamak fueled with polarized deuterium and tritium is whether non-depolarizing boundary materials are required. Such materials would be used for the limiter or divertor surface and for some or all of the first wall surface. If such materials are not required, then impurity control issues are essentially the same as for conventionally fueled reactors. It appears likely, however, but not certain, that non-depolarizing materials would be required, in which case impurity control may be much more difficult. We discuss briefly in this section the problems that non-depolarizing materials may present in impurity control, and speculate on a possible means of using conventional materials with polarized fuel.

In general, impurity control in tokamak reactors poses difficult design problems due to the high heat and particle loads expected on the helium removal system. Various boundary materials have been proposed as suitable for different impurity control configurations and different plasma edge temperatures. These include, for example: 1) the use of a tungsten coated divertor⁽¹⁾ for low edge temperature to minimize deuterium/tritium (DT) sputtering and disruption induced melting; 2) the use of a beryllium coated medium for limiters with high edge temperatures⁽²⁾ to minimize self-sputtering; 3) the use of copper-lithium alloy coatings on the limiter or divertor⁽³⁾; and 4) the use of clean, uncoated stainless steel or vanadium first walls. All metals and most non-metals will depolarize impinging hydrogen species. They are therefore probably unacceptable as the surface material for a limiter or divertor in a polarized fuel reactor.⁽⁴⁾

The first wall material requirements are uncertain because in some plasma regimes i.e., low edge temperature and high deuterium/tritium density, the DT charge exchange flux tends to be confined to a region close to the limiter or divertor. In this case a non-depolarized coating may be required only in the vicinity of the limiter/divertor and not on the whole first wall.

As discussed further in Section IV.C, there are three materials that may have suitably low depolarization rates. These materials are carbon, boron nitride (BN), and silicon carbide (SiC). Of these, carbon appears more suitable than the other two compounds from the impurity control viewpoint since some of the possible problems with BN and SiC as boundary materials may be severe. These potential problems include: (1) inadequate thermal conduc-

tivity particularly under neutron irradiation; (2) high DT sputtering coefficients; (3) unequal erosion/redeposition rates of the constituent elements leading to an unsuitable surface composition⁽⁵⁾; and (4) flaking, cracking, and inadequate bonding of the original or redeposited material.

Carbon has better thermal properties than the other two materials; its use eliminates the concerns about stoichiometry. Carbon has been proposed as a candidate surface material in several reactor studies but there are concerns regarding its sticking properties, its chemical sputtering, and the net erosion rates. In general, it is not possible to conclude that a non-depolarizing material could not be made to function acceptably for impurity control. However the limited number of acceptable materials may severely restrict the design options in an already difficult area.

Because a non-depolarizing material may not be acceptable, we briefly examined the possibility of using conventional edge materials. This possibility is based on the idea that while metals and most other materials will quickly depolarize impinging hydrogen (in milliseconds), it may be possible that the core plasma (where almost all the fusion occurs) would remain sufficiently polarized to achieve an acceptable enhancement of fusion power. This hypothesis is based on transport studies of tokamaks which predict a substantial difference in core and edge particle confinement times. For example, the respective confinement times are reported to be ~ 5 s and ~ 50 ms respectively⁽⁶⁾ in one study. Therefore it may be possible that depolarized fuel in the edge may mix with the polarized fuel in the core at a slow enough rate so that the core is maintained in a highly polarized state. This scenario would probably require plasma fueling by injecting polarized fuel pellets as close to the core as possible. It also may be possible to optimize plasma density and temperature profiles to augment the core/edge separation. A study using a 1-D plasma transport code could be used to analyze this issue but this was not possible for the limited scope of this study.

To determine the degree of core depolarization that is acceptable, the effect of partial polarization of the fuel on the total fusion power enhancement was computed. Following the notation of Ref. (4) the enhancement ratio is expressed as:

$$\frac{\delta}{\delta_0} \approx a + \frac{2}{3} b + \frac{1}{3} c \quad (\text{IV.B-1})$$

$$\text{where } a = d_+ t_+ + d_- t_- \quad (\text{IV.B-2})$$

$$b = d_0 \quad (\text{IV.B-3})$$

$$c = d_+ t_- + d_- t_+ , \quad (\text{IV.B-4})$$

and d_+ , d_0 and d_- are respectively the fractions of D nuclei polarized parallel, transverse, and antiparallel to $\vec{B}$ and t_+ and t_- are the corresponding fractions of T nuclei. We can define a polarization fraction f :

$$d_+ \equiv f \text{ where } \frac{1}{3} \leq f \leq 1 , \quad (\text{IV.B-5})$$

and the limits on f represent completely unpolarized (randomly-polarized) fuel and completely polarized fuel respectively. We assume that the remaining deuterium is distributed equally in the other two states as

$$d_0 = d_- = \frac{1-f}{2} \quad (\text{IV.B-6})$$

and that the tritium polarization fraction is related to the D fraction as

$$t_+ = \frac{3}{4} f + \frac{1}{4} \text{ and } t_- = 1 - t_+ . \quad (\text{IV.B-7})$$

The enhancement ratio is then:

$$\frac{\delta}{\delta_0} = \frac{3}{4} f^2 - \frac{1}{2} f + \frac{3}{4} . \quad (\text{IV.B-8})$$

This relation is plotted in Fig. IV.B-1. As shown, the fusion cross section enhancement is only appreciable for high values of the polarization fraction. This tends to argue against the use of conventional boundary materials since, even at an 80% polarization fraction in the core, the fusion enhancement would be reduced by $\sim 50\%$. Nevertheless, there may be tradeoffs possible between the fusion enhancement benefits of polarizing fuels and the impurity control design problems.

Figure IV.B-1. Enhancement ratio as a function of polarization fraction.

References for Section IV.B

- (1) INTOR - International Tokamak Reactor, Phase One Report, ST J/PUB/619, IAEA, Vienna (1982).
- (2) C. C. Baker, et al., "STARFIRE - A Commercial Tokamak Power Plant Study," Argonne National Laboratory, ANL/FPP-80-1 (1980).
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IV.C Surface Materials in the Plasma Chamber

IV.C.1 Requirements

The surface materials used for polarized plasmas must meet the general requirements for all plasma side materials plus the special requirement of minimizing the depolarization of particles which strike the surface. The general requirements are shown in Table IV.C-1.⁽¹⁾ The surface sputtering properties are probably the most important in selecting a class of materials for specific plasma edge conditions, since sputtering has a direct influence on plasma operation. The other properties impact primarily on the lifetime and economics of the plasma side systems. If the surface material is not used as a structural material, i.e. it is supported by a different structural material, then the mechanical properties are of secondary importance. The surface material will not carry a mechanical load and must only retain its structural integrity over the lifetime of the component. The edge temperature is the primary parameter which determines the class of surface material to be used.⁽²⁾ At high edge temperatures (> 100 eV) low-Z materials such as Be, C, and SiC are favored. At low edge temperatures, high-Z materials W and Ta are favored. The choice of a plasma side material is made more difficult by the lack of data on the candidate materials. In general, the data base for the relevant properties can be classified as poor.⁽³⁾

In addition to the properties shown in Table IV.C-1, there are a number of desirable properties for minimizing the depolarization of particles striking the surface. A summary of these properties is shown in Table IV.C-2.⁽⁴⁾ These requirements will greatly reduce the number of potential surface materials. The requirements of a high temperature, non-metallic low-Z material, with a cubic symmetry, is highly restrictive but can potentially be met by a material such as SiC. Graphite may also be a reasonable choice. In Ref. (4), the authors stated that hydrogenated amorphous semiconductors might be considered as candidate materials. Unfortunately, the data needed to evaluate materials for polarized plasmas is not available.

There are several depolarization mechanisms whose magnitudes are unknown. Most important is the possible role of large concentrations of surface paramagnetic impurities. The needed information could possibly be obtained by NMR techniques or by scattering low energy polarized alkali nuclei

Table IV.C-1. General Requirements of Plasma Side Materials

Property	Desirable Value	Purpose
Thermal conductivity	High	Minimize thermal stress
Thermal expansion	Low	
Young's modulus	Low	
Specific heat	High	Minimize effect of thermal shock
Melting point	High	Reduce disruption losses
Yield strength	High	Maximize allowance stress
Ultimate tensile strength	High	
Uniform elongation	High	Maximize ability to withstand off-normal events
Total elongation	High	
Swelling	Low	Minimize dimensional and physical property changes
Creep	Low	Minimize dimensional changes
Fatigue	Low	Prevent catastrophic failure
Crack growth	Low	
Activation	Low	Maximize safety
Tritium permeation and retention	Low	Maximize safety - reduce inventory
Sputtering	Low	Reduce wall thinning and plasma impurities

Table IV.C-2. Desirable Properties of Wall and Limiter Materials
for Polarized Plasmas⁽⁴⁾

Property	Comments
High temperature	Reduces dipolar, quadrupole, and paramagnetic relaxation
Nonmetallic materials	Eliminates relaxation due to inelastic spin-flip collisions with conduction electrons
Lattice nuclei have small or zero magnetic dipole moments	Decrease diffusional relaxation
High H and He solubilities	Avoid blistering of wall which can lead to internal sources of diatomic molecules and spin-rotation relaxation
Rapid surface desorption by molecular recombination	Minimize residence time by allowing nuclei to escape rapidly
Low-Z atomic composition	Avoid high-Z impurities in plasma that lead to high radiation loss
Low surface and bulk concentrations of paramagnetic impurities	Not easily controlled because of constant erosion and redeposition
Cubic lattice symmetry	Noncubic lattice sites can depolarize deuterons by quadrupole relaxation

off carefully prepared surfaces in an ultra high vacuum chamber. At this point it is not possible to positively identify a material that meets all of the requirements for a plasma side material for polarized plasmas.

IV.C.2 Materials Data

In the absence of adequate data it is necessary to speculate on the possibility of finding a suitable plasma side material. For long term applications, the material lifetime is likely to be limited by radiation damage effects. SiC and graphite, which are considered to have high resistance to radiation damage compared with other non-metals, will be used to illustrate the concerns about radiation damage. Some of the unirradiated properties of SiC and graphite are shown in Table IV.C-3.⁽²⁾ In general, both materials at low temperatures have good thermal properties and a low coefficient of thermal expansion which translates into an ability to accommodate high heat fluxes. Graphite has the best thermal shock resistance of all materials. At elevated temperatures the thermal conductivity is reduced considerably in both materials.

Radiation damage will limit the lifetime of non-metals by degrading the thermal properties, by inducing dimensional changes, and by degrading the mechanical properties. Figure IV.C-1 illustrates how the thermal conductivity of SiC is degraded with irradiation.⁽²⁾ The effect of radiation is most pronounced at low temperatures, but even at 1000°C the thermal conductivity is reduced by a factor of two. The reduced conductivity means that the heat flux limit to the material will be reduced and that thermal stresses will increase. Irradiated graphite will experience similar reductions in thermal conductivity with a predicted lower limit of 30 W/mK which is independent of temperature.

Neutron irradiation will induce dimensional instability in SiC and graphite, but the type of change will be considerably different between the two materials. The swelling of silicon carbide produced by irradiation can be divided into two temperature regimes. For irradiation at temperatures below about 1000°C, irradiation causes a lattice expansion that saturates at relatively low fluences (Fig. IV.C-2). The resulting swelling is temperature dependent, with the saturation volume falling from about 3% at room temperature to near 0.3% at 1000°C. For irradiation at high temperatures, voids

Table IV.C-3. Properties of SiC and Graphite⁽²⁾ at Room Temperature

Property	β -SiC (CVD)	Graphite
Density (g/cm^3)	3.2	1.8
Thermal conductivity (W/m-K)	67	170
Thermal expansion ($\times 10^{-6}/\text{K}$)	2.9	4.3
Tensile strength (MPa)	360	40
Young's modulus (GPa)	430	6.5
Specific heat (J/kg-K)	690	710

Figure IV.C-1. Thermal conductivity of unirradiated SiC and irradiated SiC at the irradiation temperature as a function of temperature (fluences between 10^{25} and 10^{26} n/m²).

Figure IV.C-2. Irradiation-induced expansion of SiC as a function of irradiation temperature (fluences between 3×10^{24} and $5 \times 10^{25} \text{ n/m}^2$).

form (as in the case in metals), and higher swelling levels are projected at higher fluences. Hopkins, et al.⁽⁵⁾ predict that at irradiation temperatures above about 1300 K, void swelling will severely limit the useful lifetime. Void swelling at elevated temperatures will limit the operating temperatures of SiC to $\lesssim 1000^{\circ}\text{C}$. The effect of radiation on linear distortion in graphite is shown in Fig. IV.C-3. In contrast with other materials, graphite initially densifies and then begins to expand without limit. The useful lifetime of graphite is usually specified as the point at which the linear distortion returns to zero. As shown in Fig. IV.C-3, lower temperature operation provides a longer swelling lifetime. At 500°C , the lifetime is estimated to be $\sim 4 \text{ MW-y/m}^2$, and at 1000°C it is estimated to be only $\sim 1 \text{ MW-y/m}^2$.⁽²⁾

The mechanical properties of graphite will degrade at about the point where positive swelling begins. Therefore, the lifetime for mechanical properties is the same as for swelling. The neutron data for pyrolytic SiC indicates that the strength is not affected at dose levels of 10^{26} n/m^2 .⁽²⁾ Reaction bonded SiC does exhibit reduced strength at low fluences, but the strength partially recovers at higher fluences. Unfortunately, it is not possible to accurately predict the mechanical property lifetime for SiC because of the lack of high fluence data.

IV.C.3 Conclusions

The use of non-metals for plasma side materials is expected to result in reduced lifetimes compared with metals. Graphite will likely have a lifetime of $1\text{--}4 \text{ MW/m}^2$, depending upon the operating temperature. On the other hand, SiC could exhibit an extended radiation damage lifetime. High fluence data is needed, however, to make a realistic lifetime estimate. Of course, it has to be determined whether these materials have suitable properties for minimizing depolarization.

Since a limited lifetime is anticipated, it is probably advisable that allowances be made for frequent replacement. This may not be a serious problem, because the great majority of particles are expected to strike only the limiter or divertor plates and not the first wall. Hence, only the limiter or divertor need to be designed for rapid and frequent replacement.

Figure IV.C-3. Typical graphite design curves for a nuclear reactor. Graphite is assumed isotropic.

In conclusion, if special non-metals are required on plasma side surfaces to minimize depolarization of particles, then short lifetime due to radiation damage is a major concern. The overall impact of a reduced lifetime upon reactor operation and maintenance needs to be assessed.

References for Section IV.C

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V. SUMMARY OF BENEFITS/LIMITATIONS ON THE USE OF POLARIZED FUELS

V.A Capital Cost Tradeoffs

In assessing the capital cost impact of using polarized fuels, several assumptions were made to obtain baseline values: 1) that the reactor was tenth of a kind; 2) that the balance of plant scaled as $(P_f)^{0.7}$ normalized to STARFIRE⁽¹⁾ where P_f is the total fusion thermal power; 3) that the current driver scaled at \$1/watt; 4) that ~ 75 MW of current driver power is needed for startup; and 5) that pellet injectors are the reference fueler. In addition, two reference cases were considered, a STARFIRE group of reactors and a second set having a smaller radius and a higher beta, in order to assess how factors like size and beta might influence the capital costs.

A number of alternative cases have been considered for the two reference cases - see Table V.A-1. For the STARFIRE-like reactors (based on moderate β obtained in the first stability regime), the alternative cases examined the possible benefits from polarized fuels in terms of lower magnetic field (STAR-B), lower β requirements (STAR- β) and higher operating temperatures (STAR-T). The advanced reactor and its alternatives (designated High-Beta and MOD, and based on second stability regime physics) included the same cases mentioned above, plus variations in first wall loading (MOD-W) and reduced reactors site (MOD-R). These various cases are discussed further in Section III.

For the STARFIRE reactor, the maximum magnetic field is 11.1 Tesla whereas the higher beta reference reactor has a field of 6 Tesla. The difference in the capital cost of the magnets for these two reference systems is ~ \$200 M (\$217 M to \$19.5 M). In addition the magnet cost decreases from 11% to 3% of the total cost of the reactor plant as the fusion power and reactor size is decreased. Since the effects of polarized fuels have not yet been considered, this difference illustrates the effect that a substantial change in the size of a reactor or in its magnetic field can play.

In the different alternatives for an advanced reactor, we have considered two cases, i.e., MOD-R and MOD-B, in which the size of the reactor and the magnetic field were each varied from the reference. In Table V.A-1, the magnet capital costs are shown for the advanced reactor for these two alternatives, \$15.6 M and \$16 M respectively, both down ~ 18% from the \$19.5 capital

Table V.A-1. Cost Comparison of the Alternatives Possible With Polarized Fuels for Two Reference Reactors

First Stability, Large Radius				
	STARFIRE	STAR-B	STAR-β	STAR-T
Magnets (\$ M)	217	176	217	217
(CD - 75) ^a (\$ M)	15	-	-	-
Polarized Fuel (\$ M)	-	< 30	< 30	< 30
Subtotal (\$ M)	232	206	247	247
% Total Cost ^b	11.2	10.1	11.8	11.8
Total Cost ^b (\$ M)	2073	2046	2087	2087
P _{net} (MW)	1200	1240	1228	1256
Direct Cost Elec. (\$/W)	1.73	1.65	1.70	1.66

Second Stability, Small Radius						
	High-Beta	MOD-B	MOD-β	MOD-T	MOD-W	MOD-R
Magnets (\$ M)	19.5	16	19.5	19.5	19.5	15.6
CD ^a (\$ M)	5	-	-	-	5	-
Polarized Fuel (\$ M)	-	< 15	< 15	< 15	< 20 ^c	< 15
Subtotal (\$ M)	24.5	< 31	< 34.5	< 34.5	< 44.5	< 30.6
% Total Cost ^{d,e}	2.6	3.3	3.7	3.7	3.6 ^e	3.3
Total Cost (\$ M)	930	937	940	940	1248 ^e	936
P _{net} (MW)	540	578	555	588	865	574
Direct Cost Elec. (\$/W)	1.72	1.62	1.69	1.60	1.44 ^f	1.63

^a Assumed cost \$1/watt; greater cost savings if \$2-\$4/watt.

^b BOP = \$1840 M.

^c The increased power requires a higher fueling rate, thus more polarized fuel.

^d BOP = \$906 M.

^e BOP = \$1203 M.

^f If increased maintenance on inner first wall is required, then the \$/W may equal \$1.72.

cost of the reference system. For the larger reactor, STARFIRE, a similar case is shown for a lower magnetic field. Here the capital cost of the magnet system decreases from \$217 M (the reference) to \$176 M, an $\sim 19\%$ decrease.

In Table V.A-1, the capital cost of the major systems affected by the use of polarized fuels are shown for the two reference reactors. Since the pellet fuelers are considered as part of the reference case, the only additional capital cost is that for the system needed to produce polarized fuel. The values listed for polarized fuel production, $< \$30$ M for the 1200 MW_{net} (first stability reactor) system and $< \$15$ M for the 540 MW_{net} (second stability reactor) system, are the estimated capital cost for a system based on cryogenic magnets and microwave units capable of producing $4-12 \times 10^{21}$ particles/s. The total capital cost of the fuel production system is equivalent for the three alternatives based on the STARFIRE reference. This is also true for the five alternatives in the higher beta system.

A benefit noted for the direct cost of electricity for each of the alternatives is that it is lower than the reference case. For most cases, the reduction in unit direct capital cost is small ($\$1.72/\text{watt}$ to $\$1.62/\text{watt}$). For the case where the wall loading is increased, case MOD-W, it is significantly reduced, from $\$1.72/\text{watt}$ to $\$1.44/\text{watt}$. However, this result is more indicative of a benefit from increased wall loading. A detailed assessment of a conceptual reactor design would be needed to determine if there was an increased operating cost due to a shorter first wall lifetime associated with the higher wall loading.

The use of polarized fuels decreases the cost of the current driver since the increased reactivity lowers the rf requirements. However, for steady state operation, a low frequency fast wave system may not be useable with polarized fuels since its frequency has a high probability of depolarizing the fuel.

V.B Other Tradeoffs

If polarized fuels are used, there are several areas in which improvements are noted which cannot be easily assessed as capital costs. Examples include the possible increase in safety due to a reduction in the stored energy in the magnets and a reduction in the effect of a disruption.

For the systems considered, the cases listed as MOD-B and MOD-R both have lower stored kinetic energy, 4.1 GJ and 3.0 GJ respectively from the reference case of 5.0 GJ. The structure needed to withstand these forces in the event of an accident would be either cheaper for the same level of safety or more resistant to deformation for the same cost design.

In Section III.B.1.1, an estimate of the damage during a 100 ms disruption is noted for some metals. In addition if one considers graphite, the amount of vaporized material during a 1 ms disruption at an energy density of 700 J/cm^2 is $\sim 37 \mu$. In the MOD-B reactor, only an energy density of 572 J/cm^2 would be reached so $\sim 33 \mu$ would be vaporized. For longer disruptions, 5 ms and 20 ms, one might expect 20μ and $< 5 \mu$ of material to be vaporized respectively. Thus, the thermal response after a disruption would be enhanced for at least one of the cases considered.

V.C Neutronics Benefits

The use of polarized fuels does not significantly impact the total breeding ratio of the blanket ($\pm 1\text{-}2\%$) for two cases considered: polarization of only deuterons and polarization of both the deuterons and the tritons.

For the case where only the deuterons are polarized, the net neutronic effect is that the frequency of replacing the first wall increases by 20% and the thickness of the outboard shield has to be increased $\sim 4 \text{ cm}$.

When both deuterons and tritons are polarized, the first wall's lifetime is increased by 5%, but $\sim 7 \text{ cm}$ additional shielding is required on the inboard section. Other benefits for this case are that the spatial distribution of various nuclear responses is smoothed and the total nuclear heating in the first wall is reduced by $\sim 8\%$.

V.D Conclusions

The use of polarized fuels in a commercial reactor can increase its performance. However, the sum of all benefits does not result in a significant improvement in reactor economics. This is especially true where polarization will not be 100%, which was assumed for all calculations in this report. As seen in Fig. IV.B-1, the benefits of polarized fuels are quickly lost if polarization is $< 95\%$. Therefore, the primary value of polarized fuels appears to

be as an option which can be applied in a fusion reactor design if a required condition cannot be achieved in other more standard operating modes.

References for Section V

- (1) C. C. Baker, et al., "STARFIRE - A Commercial Tokamak Fusion Power Plant Study," Argonne National Laboratory, ANL/FPP-80-1 (1980).

VI. RECOMMENDATIONS

Critical issues concerning the application of polarized fuels to fusion reactors include: 1) the effective use of metals as first wall materials when polarized fuels are present; 2) the extent of depolarization with various rf systems; and 3) a method of producing $\geq 10^{22}/s$ amounts of polarized fuel continuously. The primary reasons why these issues are important are:

- 1) The use of metal wall materials will reduce maintenance requirements at the limiter and divertor since metals have longer expected lifetimes.
- 2) One of the greatest benefits of polarized fuels is the reduced current drive requirement. If no system is workable, this benefit disappears.
- 3) This report assumed that $10^{22}/s$ particles can be easily produced. Since this has not even been demonstrated for 10^{12} quantities of tritium, this is a significant area of technology which needs development.

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