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ABSTRACT

A comparison of the key features of the D-^{3}He Apollo and the DT ARIES fusion power reactor designs is made. The reduction in neutron production from the D-^{3}He reaction has a major effect on the performance of tokamak reactors. One of the biggest impacts is the low radiation damage rate in D-^{3}He systems which allows a permanent first wall to be utilized. The reduction in radioactivity in D-^{3}He reactors has a particularly advantageous effect on the storage of wastes as well as on the safety to the public in the event of the worst conceivable accident. The more difficult D-^{3}He physics requirements are offset by the technological advantages of using this fuel in place of the DT cycle.

I. INTRODUCTION

The use of thermonuclear fusion to generate electricity has been studied since 1951. While there have been a multitude of confinement concepts proposed to produce that electricity, one thing that has stayed essentially constant is the fuel cycle. The use of deuterium (D) and tritium (T), either in magnetically or inertially confined plasmas, has been the subject of over 50 major reactor designs published since 1970.[1] However, there has been a growing disenchantment with this fuel cycle over the past decade because of the problems associated with handling the 14 MeV neutrons which carry 80% of the thermonuclear energy.[2,3] Scientists all over the world have been searching for a better way to provide society with a clean, economical, and safe supply of energy for centuries to come.[4–7] The purpose of this paper is to present a more attractive alternative to our present DT fusion path and that is to eventually use the D-^{3}He fusion cycle.

II. WHY WOULD WE WANT TO CHANGE?

There is a simple logic sequence that one can follow in analyzing whether one should stay with the DT or move, in the long run, to the D-^{3}He fuel cycle (see Fig. 1). The first question to ask is:

"Will the D-^{3}He fuel cycle produce electricity significantly cleaner and safer than the DT cycle?"

If the answer to that question is no, then because of the well known terrestrial scarcity of ^{3}He fuel resources or the increased difficulty in the D-^{3}He plasma physics, one should stay with the DT fuel. If one can show that there are significant safety and environmental advantages to the D-^{3}He cycle, then one must face the next question.

"Can we get the ^{3}He fuel economically?"

If the answer to that question is no, then regardless of its attractive safety and environmental features, one would stay with the DT cycle. On the other hand, if one could obtain the ^{3}He economically, then we would have to consider the next question:

"Can the physics problems be solved in a timely fashion?"

Having an attractive fuel cycle and plenty of fuel is no good if it would take 50 years or more, beyond that required for the DT cycle, to solve the plasma physics problems. On the other hand, if the plasma physics solutions can be obtained in no more than, say 10 years, after the similar solution are obtained in the DT case, then we must ask ourselves:

"How would the present fusion program change?"

The main objective of this paper is to concentrate on the first question and try to answer it by comparing two recent fusion power plants, each based on a different fuel cycle. The question of the fuel cycle has been addressed elsewhere[8] and the question of the development time for the fuel cycles can logically follow this paper.

III. FRAMEWORK FOR COMPARISONS

Because there have been no convincing studies to show that one could burn the D-^{3}He fuel economically in inertially confined systems, this study will concentrate on magnetic confinement only. The choice of the specific magnetic systems to compare is a bit more complicated. A tokamak confinement approach would be the most relevant in the current climate of research around the world but that choice does bias the results

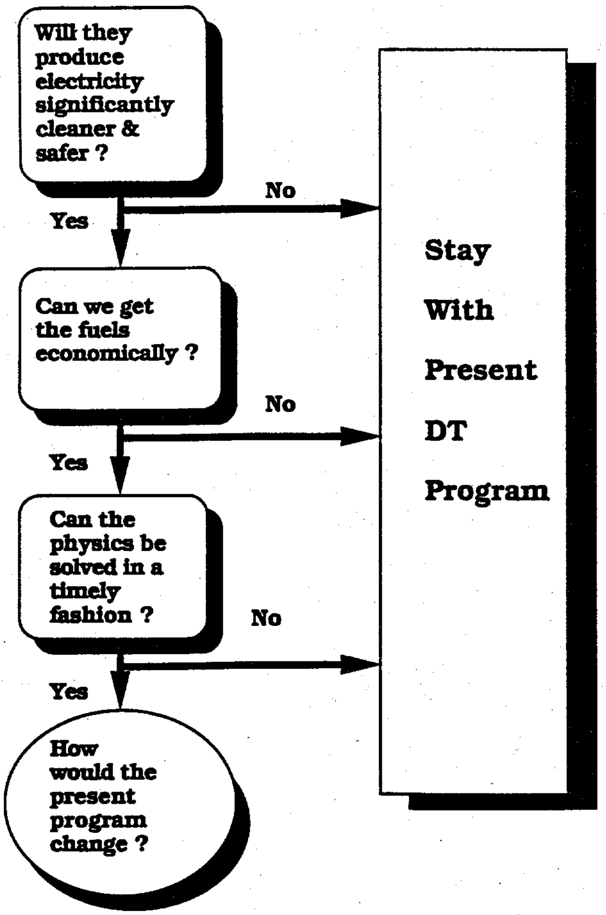

Fig. 1. Logical questions about the use of advanced fuels versus DT.

against the D-^{3}He fuel cycle. A high beta (ratio of the plasma pressure to the magnetic pressure) system, e.g., a FRC, Tandem Mirror, Electrostatic, Multipole, or RFP confinement approach, would be much better for the ^{3}He cycle. Unfortunately, most of the research on the above concepts has been curtailed in the U.S. and the effort outside the U.S. is at a relatively low level. Therefore, the tokamak was chosen for this study even though it must be recognized at the outset that if the D-^{3}He cycle can compete with the DT cycle in tokamaks, it can be even much more favorable in the other high beta systems.

The choice of specific DT designs to compare against was between the STARFIRE[9] and the ARIES-I[10] conceptual studies. The STARFIRE design is a much more conservative system, both from the standpoint of physics and technology, than the ARIES-I study. However, the ARIES-I project was completed in 1991 (vs. 1980 for STARFIRE) and therefore felt to be more representative of the current physics data base. The choice of the D-^{3}He design was relatively easy as there has been only one detailed, first plasma stability regime, tokamak in the literature, namely the Apollo series.[11–14]

TABLE I

A Comparison of the Key Features of 1000 MWe Tokamaks – the DT Based ARIES-I and the D-^{3}He Based Apollo

Parameter	Units	Apollo[14]	ARIES-I[10]
Fuel cycle		D-^{3}He	DT
Aspect ratio		3.15	4.5
Major radius	m	7.89	6.75
B_{max}	T	19.3	21.3
$\langle T_i \rangle$	keV	57	20
Toroidal beta	%	6.7	3.2
Troyon coefficient		3.5	3.2
$n\tau_E$	10^{14} s/cm^{-3}	29	3.7
Current	MA	53.3	10.2
Average neutron wall loading	MW/m^2	0.1	2.21
Structural material		Low Activation Steel	SiC
Heat transport fluid		Organic @2 MPa	He @10 MPa
Power conversion		Rectenna + Rankine	Rankine
Maximum first wall temperature	°C	550	1000
Thermal power	MWth	2144	2543
Cost of electricity	1991 mills/kWh	77	80

It is only possible, in this short paper, to list a few of the more important parameters of each design (see Table I) and the rest of this paper will concentrate on the environmental and safety factors.

Aside from being slightly bigger in size, the maximum magnetic field is smaller in Apollo. The average ion temperature, the required $n\tau_E$, and the plasma current are all larger in Apollo than the values in ARIES-I. Startup[14] and fueling[15–17] issues are covered elsewhere but both appear to be managable within the current physics concepts. The extremely small neutron wall loading (by a factor of over 20) allows the use of an organic coolant in the Apollo reactor and, as shown later, this feature will have a major impact on the environmental and safety features of the D-^{3}He reactors. The high fraction of power in synchrotron radiation also allows direct conversion of thermonuclear energy to electricity in Apollo. This higher efficiency is achieved at relatively modest temperatures compared to the DT system and the final cost of electricity is in fact slightly lower in the advanced fuel system.

TABLE II

Summary of the Radiation Damage Parameters in
the ARIES-I[10] and Apollo-L3[14] Reactors

Parameter	Units	Apollo (D-^{3}He)	ARIES-I (DT)
First wall structural material		Low activation stainless steel	SiC
Average heat flux to divertor	Watts/cm^2	330	250
Neutron wall loading			
	MW/m^2 average	0.1	2.21
	MW/m^2 peak	0.14	3.34
Displacement damage			
	dpa per MWy/m^2	22.2	$\approx$10
	Peak dpa/FPY	3.11	$\approx$33
	Peak dpa @ end of life	93 @ 30 FPY's	$\approx$200 @ 6 FPY's
Transmutation rates			
	appm He per MWy/m^2	115	1156
	appm H per MWy/m^2	381	618
	Peak appm He/FPY	16.1	3861
	Peak appm H/FPY	53.3	2064
	Peak appm He @ end of life	483 @ 30 FPY's	23,120 @ 6 FPY's
	Peak burnup @ end of life %	Transmutation not burnup	1.7% C 0.08% Si

IV. RADIATION EFFECTS

One of the major differences between DT and D-^{3}He reactors is the level of neutron irradiation to the reactor structural materials. Key parameters of the neutron exposure are given in Table II.

It is clear that the low neutron flux associated with the D-^{3}He reaction greatly reduces the dpa rate as well as the production of helium and hydrogen gas atoms in the first wall materials. Steels, tested at the maximum reactor damage level of $\approx$90 dpa $\approx$550°C, while containing $\approx$500 appm He, have already been shown to perform satisfactorily.[18] It is also worth noting that if the SiC reaches its hoped for life of 20 MWy/m^2, almost 2% of the carbon atoms will literally be turned to gas and every atom will have been displaced on the order of 200 times! There is no data at these conditions from which to make predictions of the ability of SiC to maintain its strength and vacuum sealing properties at temperatures of 1000°C. From this it is easy to see why a major materials development program is required before DT fusion power plants made from SiC could even be considered.

V. RADIOACTIVITY

In order to calculate the level of radioactivity induced in the structures, one must use the appropriate neutron spectra and the actual blanket and shield structure. Previous studies[19,20] have discussed the details of such analyses and only the results will be listed here.

The normal indicator of the long term level of radioactivity in a nuclear system is the manner in which the waste can be stored. The crude differentiations of "near surface" and "deep geological" disposal have been supplemented with Class A,B,C, ..., defined in more detail elsewhere.[19] For the purposes of this paper, the near surface category of Class A waste is the most desirable because it requires only minimal packaging and it only has to be monitored for 100 years. Class C, while still acceptable, requires more substantial packaging and a 500 year monitoring time. Obviously, any near surface burial scheme is preferable to a deep geological facility.

The categorization of the long term waste from the DT (ARIES-I) and D-^{3}He (Apollo reactors) is summarized in Table III. It is shown that the modified HT-9 and SiC structural materials qualify for Class A, near surface burial waste, as does the isotopically tailored W on the divertors of both reactors. However, the Li_2ZrO_3 only qualifies for Class C waste even if one could isotopically tailor approximately 150 tonnes of Zr over the life of the reactor to the following composition:

Isotope	Natural	Tailored
^{90}Zr	51.46	0.06
^{91}Zr	11.23	0.01
^{92}Zr	17.11	99.91

TABLE III

The Categorization of Long Term Waste From Fusion Reactors

	Apollo (D-^{3}He)	ARIES-I (DT)
Structural material	Low activation ferritic steel	SiC
WDR* Class A rating	0.88	—
WDR* Class C rating	—	0.1
Neutron multiplier	None needed	Be
WDR* Class A rating	None needed	$\ll$0.1
Breeder material	None needed	Li_2ZrO_3 (99.9% ^{92}Zr)
WDR* Class C rating	None needed	0.05
Divertor coating	W (90% ^{183}W)	W (90% ^{183}W)
WDR* Class A rating	0.1	—
WDR* Class C rating	—	0.1

*If the WDR rating is <1.0, then the material qualifies for burial in that category.

Similarly, the tungsten isotope ^{186}W must be significantly reduced by isotopic tailoring to the composition below in order to achieve near surface waste burial status:

Isotope	Natural	Tailored
^{180}W	0.00135	0.02
^{182}W	11.23	4.44
^{183}W	14.4	90.0
^{184}W	30.6	5.18
^{186}W	28.4	0.36

The technology required to isotopically tailor 100's of tonnes of W and Zr per year still has to be developed for DT reactors. Thus, it is possible that this technology research alone could require a decade of development after the announced physics breakeven point is first reached. Such a long R&D time is the reason that many think that D-^{3}He will in fact result in a lower cost of electricity in the long run.

VI. SAFETY

A common method of assessing the overall safety of a nuclear power plant is to calculate its Level of Safety (LSA) rating as outlined in previous papers.[21,22] There are 4 levels to consider starting from the worst (LSA-4), where active measures must be used to prevent fatalities. The most favorable LSA rating is the #1 level, which basically says, there is no conceivable way that energy in the reactor could mobilize enough radioactivity to cause any civilian casualties.

A measure of the radioactive inventories, potential sources of radioisotope mobilization and estimated offsite effects of the worst conceivable accidents is given in Table IV.

TABLE IV

A Comparison of the Key Safety Features For DT and D-^{3}He Fusion Reactors

	Apollo (D-^{3}He)	ARIES-I (DT)
Decay heat from in vessel components at shutdown	5.62 MW	Not given
T_{max}	600°	1000°C
Offsite MEI* due to LOCA	4.4 Rem	130 Rem (Assumes only 2% of modules fail)
T_{max} in LOCA with organic fire	1200°C	NA
Offsite MEI* dose due to LOCA and organic fire	126 Rem	NA
LSA rating	1	2**

* MEI ≡ Maximum exposed individual
**On the basis that more than 2% of the ARIES-I modules could fail

It is important to note that the entire W divertor plate (of the new isotopic ratio) is assumed to be released along with the alloying elements in equilibrium with the temperatures listed above. Even under those circumstances, the offsite dose from an Apollo reactor to the Maximum Exposed Individual (MEI) is less than 200 Rem, the dose required for evacuation. This logic allows the D-^{3}He reactor to be given the LSA rating of 1. The less favorable LSA 2 rating was given to ARIES-I on the basis of more than 2% of the SiC modules that hold the Li_2ZrO_3 could fail.

VII. CONCLUSIONS

The technology and safety advantages of the D-^{3}He cycle have been examined and it is concluded that "Yes, the D-^{3}He fuel cycle will produce electricity cleaner and safer than the DT fusion reaction." The main reason for this statement is the greatly reduced number of neutrons which need to be handled. Most attention has been focused on the reduction in radioactivity in the ^{3}He fuel system. However, the reduction in radiation damage is perhaps even more important. Such a reduction allows:

- A "permanent" first wall to be constructed
- Less radioactive waste to handle
- A more reliable reactor performance to be anticipated
- A wider choice of structural materials.

There are also the benefits of Class A waste and the low afterheat which is intimately tied with the safety of the nuclear core. It is felt that these technological benefits outweigh the disadvantages associated with the higher $\langle T_i \rangle$, $n\tau_E$, and plasma currents that are characteristic of D-^{3}He operation in tokamaks.

VII. ACKNOWLEDGEMENT

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