FEASIBILITY OF ADVANCED FUELS

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ABSTRACT

Various fusion fuel cycles are reviewed in view of a commercial fusion reactor. Among exothermic fusion reactions, D-^{3}He fusion appears attractive because it mitigate engineering problems of DT fusion attributed to 14MeV neutrons. The safety of the reactor is inherent and environmentally sound with D-^{3}He fueled fusion. Nevertheless, the helium-3 resource is very rare and attempts to breed helium-3 seem unsatisfactory. Lunar helium-3 alone seems to provide the world a needed energy.

I. INTRODUCTION

Nuclear fusion utilizes exothermic nuclear reactions between light nuclei. Among various fusion reactions, DT reaction has the largest fusion cross-section and the lowest energy of its maximum[1]. People postulate, therefore, fusion reactors to be achieved with this fuel. Approximately 80% in a DT fusion power is, however, carried by 14MeV neutrons which damage first walls and structural materials of a reactor[2]. Further, 14MeV neutrons bring radioactivity of metallic materials. Development of materials that are sound during a reactor life is, therefore, one of key problems in developing commercial fusion reactors. Disposal of radioactive waste materials is also the big problem. An alternative approach to a commercial fusion reactor that is sound during full reactor life and environmentally acceptable can be foundby choosing fusion fuels that produce no or few neutrons.

The objectives of studying advanced fuels[3] are to reduce neutron yields drastically so as to mitigate above engineering problems. Numbers of advanced fuel cycles have been so far studied on the base of deuterium. Some concepts reduce neutron yields, however, neutron yields are still large because d-d produced tritiums react with deuteriums before they diffuse out of the plasma region. Attempts[4] to reduce neutrons entirely have been studied on the base of proton reactions. These fusion fuel cycles equire, however, physically inconsistent temperature ratio of ion temperature to electron temperature for an ignition. This comes from the fact that since the effective charge number of ions is large, radiation losses are appreciable in these fuel cycles.

Studies on advanced fuels will be reviewed and special attention will be paid to D-^{3}He fusion fuel cycle which appears attractive in views of ignition of nuclear fusion, safety, environment, and the cost of electricity.

II. VARIOUS FUSION FUEL CYCLES

Fusion reactions[1] that are relevant to our interest can be categorized by proton based fusion, deuterium based fusion, and helium-3 fusion. Fundamental nuclear reactions of respective fuel cycles are:

^{6}Li (p, α) ^{3}He	Q = 4 .02MeV
^{11}B (p, α) 2 ^{4}He	Q = 8.7MeV
D (d, t) P	Q = 4.03MeV
(, n) ^{3}He	Q = 3.27MeV
D (t, n) ^{3}He	Q = 17.6MeV
D (^{3}He,p) ^{4}He	Q = 18.4MeV
^{3}He (^{3}He, 2p) ^{4}He	Q = 12.86MeV

Since the branching ratio of D-D reaction is approximately 50:50, neutron yields/fusion power in pure D-D fusion is smaller than that in D-T fusion. D-T reaction is a compound nuclear reaction and its first resonance is at the lowest energy of 108MeV and its peak value is as large as more than 500mbarns. Therefore, a use of D-T fuels seems easiest to ignite a thermonuclear fusion.

In a Cat.D fuel cycle, deuterium is fueled into burning plasma. Neutrons, tritons, protons, and helium-3 are produced as primary reactions. A part of fusion produced tritons and helium-3 will react with deuterium before their leaking out from the plasma region. Leaked helium-3 are refueled so as to enhance fusion energy. Leaked tritons, however, are once stored in a tritium bank until they change to helium-3 through beta decay with a half life of

12.6 years, and refueled together with helium-3 extracted from the plasma. This fuel cycle is exhibited in Fig.1.

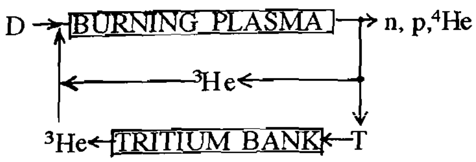

Fig.1 The Cat.D Fuel Cycle

Ultimate neutron yields reduces appreciably with this Cat.D fuel cycle compared with pure D-D or D-T fuel cycles.

In p-^{6}Li, ^{11}B, D-T, D-^{3}He, and ^{3}He-^{3}He fuel cycles, density ratio can be chosen so as to obtain a favorable fusion plasmas.

III. FIGURES OF MERITS

For the purpose of comparing various fusion fuel cycles, we will carry out parametric studies. The model we have employed for these studies are:

1) A zero dimensional plasma is assumed. That means spatial variations of plasma parameters are ignored.
2) Spitzer's formula is applied for a temperature relaxation between ions and electrons.
3) A common conductive energy loss time and convective particle loss time which is twice of conductive nergy loss time are assumed.
4) Standard formula of the bremsstrahlung and the synchrotron radiation are applied. The relativistic effects re taken account.
5) All the fusion produced charged particles are once utilized to heat the burning plasma and ultimately they diffuse out after the thermalization.

Then, a set of the continuity equations of particles and energy for respective species of fuel ions and electrons allows us the well-known ignition diagram.

A figures of merits of a burning plasma can be given by considering a socially acceptable commercial fusion reactor:

1) the triple product[5] of the electron density, energy confinement time, and averaged plasma temperature,
2) the fraction of fusion power carried by fusion neutrons in the fusion power, and
3) the fraction[3] of power carried by charged particles and conducted to a direct energy converter in the fusion power.

The triple product gives us a physical measure for the ignition and represents. Empirically, this quantity is proper to a plasma device. A fusion fuel cycle whose triple product is small means easy of achievement of ignition with this fuels. The fraction of power carried by fusion neutrons indicates how engineering problems attributed to neutrons will be mitigated. In view of the life of the structural materials, this value is expected to be less than few per cent. The fraction of power carried by charged particles and introduced to a direct energy converter is related to the plant efficiency. For a larger value of this fraction, a use of direct energy converters increases and, consequently, the output electricity increases because conversion efficiency is expected to be large from direct energy converters compared with thermal converters.

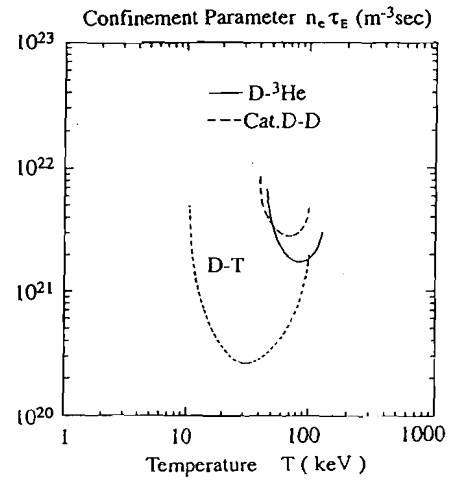

Fig.2: Confinement Parameters of Various Fusion Fuel Cycles as Functions of Averaged Plasma Temperature

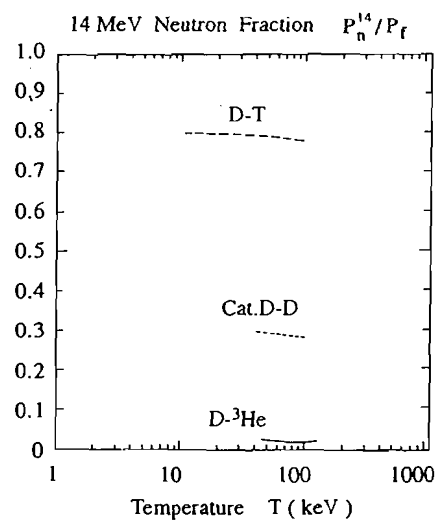

Fig.3: Power Fraction Carried by 14MeV Neutron in the Fusion Power

Figure 2 shows required confinement parameters $n_e\tau_E$ in their burning state as functions of averaged plasma temperature T.

As was mentioned, ignition is easiest in D-T fusion and its minimum triple product is $7 \cdot 10^{21}$ sec•keV/m^3. The minimum triple product of D-^{3}He fuel cycle is 17 times larger as $1.2 \cdot 10^{23}$ sec•keV/m^3, but little bit small than $1.5 \cdot 10^{23}$ sec•keV/m^3 of Cat.D fuel cycle. Since fuel cycles based on reactions p-^{6}Li, p-^{11}B, and ^{3}He-^{3}He have no ignition because of their small fusion reaction cross sections and large radiation losses attributed to their high effective z values of ions, we have ignored them.

Figure 3 is the fraction of the power carried by 14 MeV neutrons in the fusion power. The neutron fraction from D-T fusion is approximately 80%. It reduces to 30%, in Cat.D fusion. It is, nevertheless, still unsatisfactory. The 14MeV neutron fraction is only a few per cent from D-^{3}He fuel cycles, which value is enough to keep first walls to be sound during full reactor life of 30 years.

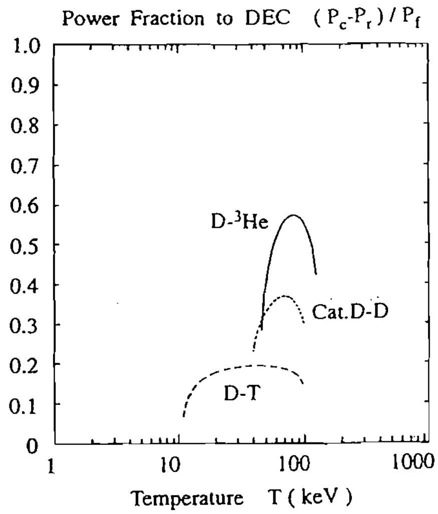

Fig.4: Fraction of Power Carried by charged Particles in the Fusion Power

Fig.4 shows the power fraction of power carried by charged particles that are introduced to a direct energy converter. In a D-^{3}He fuel cycle, the value is more than 50%. An accessibility of direct energy converters is needed to utilizes the high charged particle fraction to a fusion reactor with a high plant efficiency. This charged particle fraction depend on the plasma beta value. If plasma beta value is lower, the synchrotron radiation increases
and fusion energy shared to the charged particles deceases consequently.

The characteristics of various fusion fuel cycles are summarized as in the Table 1.

We learn on this table that the ignition is easiest and neutron fraction is largest with D-T fuel cycle. Neutron fraction is reduced drastically, however, ignition is harder from D-^{3}He fuel cycle. In other words, D-T fusion make pressure on engineering developments and D-^{3}He fusion on physics developments.

IV. HELIUM-3 RESOUCES

In order to achieve D-^{3}He fusion power plant, ^{3}He resources have to be obtained. The present level of helium-3 supply is several tens kg/y from nuclear weapons and very few from natural resources. Keeping in mind the fact that 1GWe power plant requires 50kg/y of helium-3, a certain method to supply fuel helium-3 is needed.

[Helium-3 Breeding]

It may be natural to consider a helium-3 breeding by a use of a series of reactions:

$$p + {}^6Li = {}^3He + {}^4He \quad \text{followed by}$$
$$D + {}^3He = p + {}^4He.$$

This process have to compare to their mirror reactions:

$$n + {}^6Li = T + {}^4He \quad \text{followed by}$$
$$D + T = n + {}^4He.$$

A proton bombardment on a solid or a gaseous lithium-6 target produces certain quantity of helium-3. The optimum proton energy is 1.8MeV. The ionization loss of injected protons is, however, fairly large and range of penetration is much smaller than the nuclear reaction mean free path. the obtained reaction rate is less than 10^{-9}/protons in this case. Recalling that a helium-3

	D-T	Cat.D	D-^{3}He
Density Ratio	$n_D/n_T = 1$	—	$n_{3He}/n_D = 2 \sim 1$
Confinement Parameter	$7 \cdot 10^{20}$ s/m^3	$3.5 \cdot 10^{21}$ s/m^3	$1.8 \sim 1.2 \cdot 10^{21}$ s/m^3
Average Temperature	14keV	50keV	70 ~ 60keV
Neutron Power Fraction	79%	36%	2.5 ~ 5.0%
Charged Particle Fraction	14%	34%	55 ~ 60%
Engineering Requirement	Tritium Breeding Materials	(Tritium Storage) Materials	Helium-3 Resources

produces 18.6MeV through the reaction with deuterium, the ultimate energy gain is still less than 10^{-8}.

In order to avoid a large ionization loss of injected protons, one may inject energetic protons into lithium-6 plasma. The optimum injection energy is 4MeV, in this case. The obtained helium-3 is 0.2/proton, provided that the beta value of the target plasma more than 90%. Here, we assume consistently the ion temperature of 500keV, the electron temperature of 100keV, and the confinement parameter of $3 \cdot 10^{22}\, s/m^3$. The ultimate energy gain in this case is 4.6. The problem is to obtain a lithium plasma with an extremely large confinement parameter.

[Extraterrestrial Helium-3]

In 1986, L.J.Witterberg, J.F.Santarius, and G.L.Kulcinski reported[6] presence of a large amount of Lunar helium-3. The total quantity of minable helium-3 is estimated as large as 1 million tons, which is sufficient to supply energy to the world more than several hundred years. The estimated energy gain from the Lunar helium-3 is more than 100, that value have to compared with 20 which is maximum of conventional power plant.

In a gaseous planets such as Jupiter or Saturn, presence of an infinitely large amount of helium-3 are estimated. Thus the development of D-^{3}He fusion is inevitably connected to the space developments.

V. ATTRACTIVE CHARACTERISTICS OF D-^{3}He FUSION

Conceptual design studies on D-^{3}He fueled fusion reactors have been carried out on the bases of tokamaks[7], tandem mirrors, and field-reversed configurations[8].

In these designs, the maximum heat load of the first wall is approximately $2MW/m^2$. This value can be acceptable by a use of conventional engineering.

Neutron loads of the first walls are as low as $0.1{\sim}0.3MW/m^2$. No breeding blanket is required. Since neutron fluence are very small, structural materials can be sound during full reactor life of 30 years if one selects low activation ferritic steel as structural materials. After heat of the structure attributed to the radioactive materials is also ignorable and the estimated safety assurance is level I. Thus a D-^{3}He fueled power plant is inherently safe.

Disposal of radioactive wasted materials is one of the biggest problem of atomic power. This is also serious in D-T fusion because one has to treat every 30 years more than several thousand tons of radioactive wasted materials from a 1,200MWe plant. On the other hand, an equivalent D-^{3}He fueled power plant produces 2,000~3,000tons of wasted materials whose contact dose is as low as 0.0023mSv. This value has to be compared to the allowed upper limit of 5mSv of surface disposals. Thus one finds one of environmentally acceptable power plants in a D-^{3}He fueled fusion.

Requirements on materials with extremely high stress or strong magnetic field coils have been presented by the design on a D-^{3}He fueled tokamak fusion reactor. Those problems can be resolved in a fusion reactor based on D-^{3}He fueled field-reversed configuration, where the maximum of required stress is less than 300MPa and Maximum magnetic field is 6.7T, therefore a use of conventional materials is available. .

For a purpose of achieving a lower cost of electricity, a use of direct energy converters seems preferable. For this purpose, open ended magnetic configurations of the outer plasma region such as mirrors or field-reversed configurations can be recommended as a candidate method of plasma confinement for an economical D-^{3}He fueled power plant. Development of direct energy converters installed to this plasma device is also inevitable.

VI. CONCLUSIONS

We have discussed the feasibility of advanced fuel for fusion power plant and have learned:

1) Among various fusion fuel cycles, D-T fusion seems easiest to ignite and D-^{3}He fusion appears most attractive in view of the safety and environment.
2) Development of open magnetic geometry in the outer plasma region and development of direct energy converters are needed to achieve a cheep cost of electricity from a D-^{3}He fueled fusion power plant.
3) Studies on plasma confinement suitable to apply D-^{3}He fuels are extremely important.and
4) Development of Lunar helium-3 mining and space propulsions is needed to obtain enough energy for the world in and after the 21st century.

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REFERENCES

1: Rainer Feldbacher, "*Nuclear Reaction Cross Sections and Reactivity Parameter, Library and Files,*" IAEA Wienna, 1987
2: G.A.Kulcinski, IAEA CN-33/s-3-1 (Held at Baltimore, 1977)
3: G.H.Miley," *Fusion Energy Conversion,*" (ANS,1976), Chap.2
4: J.M.Dawson,PPG-273(UCLA,Los Angels,1976)
5: J.R.McNally, Fusion Technology/Fusion Vol.2(1982) 9
6: L.J.Wittenberg, J.F.Santarius, and G.L..Kulcinski, Fusion Technology Vol.10(1986)167
7: G.L.Kurcinski, Fusion Technology Vol.15(1989)1233
8: H.Momota, A.Ishida, Y,Kohzaki, G.H.Miley, S.Ohi, M.Ohnishi, K.Sato, L.Steinhauer, Y.Tomita, and M.Tuszewski, Fusion Technology Vol.21(1992)2307