D-³He Fueled FRC Power Plant for the 21st Century

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Abstract

The principle of D-³He fueled fusion which mitigates engineering problems attributed to 14 MeV neutrons is presented as well as the requirements needed to constitute an attractive D-³He fusion reactor. The intrinsic characteristics of a field-reversed configuration appears to meet the requirements. Potential and critical issues are discussed on the bases of a comprehensive D-³He fueled FRC reactor design "ARTEMIS", which definitely offers the most attractive prospect of the energy development for the 21st century. It is inherently safe and environmentally acceptable in view of radioactivity and fuel resources. Further, the estimated cost of electricity is low compared to a light water reactor. An experimental research program needed to develop the D-³He fueled FRC fusion reactors is discussed.

Keywords:

ARTEMIS, D-³He, FRC, fusion reactor design.

1. Introduction

Progresses of the controlled nuclear fusion research have been achieved mainly with tokamaks, and the scientific feasibility experiment for controlled nuclear fusion can be expected with this concept¹⁾. Nevertheless, certain engineering problems are to be resolved before D-T fueled tokamaks being accepted as commercial fusion reactors. Development of a reasonable tritium breeding blanket is representative one. Among those, major engineering problems for commercial D-T fusion reactors (such as frequent replacement²⁾ of the first wall and structural components of the reactors, and disposal³⁾ of radioactive wastes), which are attributed to 14 MeV neutrons are very hard to resolve.

Deuterium and helium-3 fusion fuels (D-³He) have been studied for the purpose of mitigating these engineering problems attributed to 14 MeV neutrons. With those fuels, the fraction of 14 MeV neutrons in the total fusion power decreases to less than one percent and the majority of the fusion power is carried by charged particles, i.e., 14.7 MeV fusion protons and thermal ion components. By introducing these charged particles into highly efficient direct energy converters, we are able to obtain high efficiency of a D-³He fueled fusion power plant. Physics requirements on the confinement parameter $n_e \tau_E$ and the operation temperature T needed to sustain D-³He fusion reactions are as high as 1.1×10^{21} sec/m³ and around 100 keV, respectively. In order to reduce a synchrotron radiation loss and to obtain consequently high values of the plant efficiency, a large plasma beta-value ($\geq 10\%$) and an accessibility of high-power direct energy converters are required. Details of these requirements are discussed in the section 2.

Various magnetic configurations such as tokamaks, mirrors, and others have been studied

as candidates of D-³He fueled fusion. Among these, a field-reversed configuration (FRC) seems to meet well the requisites for D-³He fuels, by its intrinsic characteristics. The plasma is confined by closed lines of force for good confinement and surrounded by open lines of force suitable to install high power direct energy converters. Since an FRC has no toroidal magnetic field for plasma stabilization, an extremely high beta value (>50%) has been obtained easily in experiments. The attractive characteristics of FRCs for D-³He fuels are discussed in the section 3.

A conceptual design study of this D-³He FRC fusion reactor "ARTEMIS" has been carried out for the purpose of examining its attractive characteristics and clarifying the critical issues for commercial fusion power plants. Lunar helium-3 fuel are assumed to be relevant as fusion fuel. The results are presented in the section 4. Although various studies are needed to achieve a commercial power plant, a complete and consistent scenario with regard to physics and engineering is presented. All engineering bases applied for this design are conventional. It might be ecologically acceptable and its safety is inherent. The estimated cost of electricity is low compared to that from a light water reactor. Critical issues for developing D-³He fueled FRC reactors are also presented.

In the last section, we will summarize the principle, the potential of the concept, and critical issues needed to develop a commercial D-³He fueled FRC power plant. The main risks and experiments needed to develop the commercial power plant are also discussed.

2. Requirements for D-³He Fuels

The primary nuclear reactions⁴⁾ relevant to D-³He fuels are:

$$D + {}^3\text{He} = p + {}^4\text{He} + 18.353\text{MeV} \quad (1)$$

and

$$D + D = n + {}^3\text{He} + 3.269\text{MeV} \quad (2)$$

$$= p + T + 4.033\text{MeV} \quad (3)$$

The cross-sections of ³He (³He, 2p) ⁴He and ³He (³He, p) ⁵Li(p) ⁴He exothermal nuclear reactions are so small that they can be safely neglected in our discussions. A daughter reaction:

$$D + T = n + {}^4\text{He} + 17.589\text{MeV} \quad (4)$$

has a large nuclear reaction cross-section and other daughter exothermal nuclear reactions such as D(p, γ) ³He, ³He (t, np) ⁴He and ³He (t, d) ⁴He can be neglected too because of their small cross-sections. The cross-sections of nuclear reactions (1)–(4) are illustrated in Fig. 1. Since the D-³He reaction is comparatively dominant in a high energy region, a higher ion temperature are needed to utilize D-³He fueled fusion.

We will consider a D-³He burning plasma confined in a magnetic bottle. Parameters of the fuel plasma are obtained⁵⁾ on the bases of dominant nuclear reactions: (1)–(4) together with equations of particle balance in terms of particle injections, convective particle losses, and the change in the particle number due to nuclear reactions:

Fig. 1. Nuclear reaction cross-sections.

$$\Gamma_{inj} - \frac{n_j}{\tau_n} + \left(\frac{\delta n_j}{\delta t} \right)_{nucl.reac.} = 0 \quad (5)$$

for the j-species. The equations of the power balance described in terms of external injected powers, the energy transport, the heating power due to energetic fusion particles, radiative power losses, and the temperature relaxations:

$$P_{inj} - \frac{1}{\tau_E} \left(\frac{3}{2} n_j T_j \right) + (P)_{nucl.reac.} - P_{rad} - \frac{3}{2} n_j \left(\frac{\delta T_j}{\delta t} \right)_{relax.} = 0 \quad (6)$$

for respective ion species are supplemented. Here n_j and T_j stand for the number density and the averaged temperature in the energy unit, respectively for the j-species of the particles. Since the convective particle loss time τ_n is around twice of the energy loss time τ_E in experiments, we will assume the relation $\tau_n = 2 \tau_E$. The radiation losses from the electrons consist of bremsstrahlung radiation and synchrotron radiation. The relativistic effects on radiation powers as well as the reflection of synchrotron radiation on the metallic surfaces of the plasma chamber are taken into account⁶⁾.

The 14 MeV neutron fraction f_n , which is defined by the ratio between the fusion power P_n carried by the 14 MeV neutrons and the total fusion power P_f , is given in Fig. 2-a as a function

Fig. 2. (a) The 14 MeV neutron power fraction, (b) The radiation parameter, and (c) The confinement parameter for burning D-³He burning plasma versus the plasma temperature. The mean beta-value of 90%, $\tau_n = 2 \tau_E$, and a density ratio $n_{3He}/n_D = 1/2$ are assumed.

of the averaged plasma temperature. Note that the 14 MeV neutron fraction should be as small as possible, since they damage and induce radioactivity of the reactor materials. Further, we will introduce the radiation parameter Ψ_r defined by the ratio between the power introduced to the direct energy converters and the total fusion power. The value of the radiation parameter are exhibited in Fig. 2-b as a function of the averaged temperature. The overall plant efficiency η_p , which is defined as the ratio between the net output power P_{net} and the fusion power P_f , is expressed in terms of the efficiencies of the direct energy converter η_{DC} and that of the thermal converter η_{TH} :

$$\eta_p = (\eta_{DC} - \eta_{TH}) \Psi_r + \eta_{TH} \quad (7)$$

Since the former is usually much higher than the later, the radiation parameter Ψ_r should be as large as possible to obtain high efficiency of the plant. Finally, the relation between the

confinement parameter $n_e \tau_E$ and the averaged temperature is exhibited in Fig. 2-c. We have assumed in Figs. 2 the concentration of the fuels $n_{3\text{He}}/n_d$ to be $1/2$, the averaged beta-value defined from the external magnetic field to be 0.9 , and the synchrotron absorption coefficient that is ultimately absorbed in the first wall to be 10^{-2} . The direct loss rate of energetic fusion protons has been chosen as 32% . By achieving the plasma temperature of 90 keV and the confinement parameter of $1.1 \times 10^{21}\text{ sec/m}^3$, the 14 MeV neutron fraction decreases to 3% and the radiation parameter takes its maximum value of 72% .

Fig. 3. (a) The 14 MeV neutron power fraction and (b) The radiation parameter for burning $\text{D-}^3\text{He}$ burning plasma versus the density concentration $n_{3\text{He}}/n_d$. A plasma temperature of 90 keV , $\tau_n = 2\tau_E$, and a plasma beta-value of 90% are assumed.

Fig. 3-a and Fig. 3-b show respectively changes of the 14 MeV neutron fraction and the radiation parameter as the density ratio $n_{3\text{He}}/n_d$ changes in a $\text{D-}^3\text{He}$ burning plasma with an averaged temperature of 90 keV . The 14 MeV neutron fraction decreases to 1.4% for the case of $n_{3\text{He}}/n_d = 1$, while the effective charge number of the fuel plasma increases which brings enhanced bremsstrahlung radiation losses and consequently decreases the radiation parameter. It must be noted that those values in Figs. 3 are obtained for the averaged beta-value $\langle \beta \rangle$ of 90% and the synchrotron absorption coefficient of 10^{-2} . If $\langle \beta \rangle = 30\%$ for instance, the radiation parameter Ψ_r decreases to 50% , because the reabsorption of synchrotron radiation in the plasma decreases and consequently dissipation on the wall increases relatively. For a case of low beta plasma of $\langle \beta \rangle = 10\%$, no self-ignition is obtained in our case.

On the bases of above discussions, we are able to summarize the requirements for a low neutron $\text{D-}^3\text{He}$ burning plasma as follows:

- (1) A plasma temperature: $T = 70\text{--}100\text{ keV}$,
- (2) a confinement parameter: $n_e \tau_E > 1.1 \times 10^{21}\text{ sec/m}^3$, and
- (3) an averaged beta-value: $\langle \beta \rangle \gg 10\%$

are needed to decrease a 14 MeV neutrons to a low level of a few percent and to obtain a radiation parameter much larger than 50% . Further,

(4) accessibility of high power direct energy converters is required to make use of the attractive characteristics of $\text{D-}^3\text{He}$ fuels to a highly efficient fusion power plant.

3. $\text{D-}^3\text{He}$ Fuels in an FRC

So far various concepts for $\text{D-}^3\text{He}$ fueled fusion reactors have been studied^{7,8,9)}. For the purpose of obtaining a high efficiency of a $\text{D-}^3\text{He}$ fusion plant, however, an open magnetic geometry surrounding the fusion plasma is preferable so as possible to install high power direct

Fig. 4. A field-reversed configuration.

energy converters. On the contrary in the plasma region, magnetic lines of force should be closed to obtain a good plasma confinement. One finds those characteristics in a field-reversed configuration (FRC): A plasma is confined by a closed magnetic field and surrounded by a open lines of force (Fig. 4). Fairly high beta-values, much higher than 50 %, were so far obtained in experiments. Plasmas are stable during their operation (several m sec) if the plasma s -value defined by the ratio of their averaged ion gyration radius to the plasma radius doesn't exceed so much to unity. In experiments, the configuration keeps its intelligence as it is translated along the axis of symmetry. Since the speed of the translation is as high as the ion sound velocity, one is able to apply fueling by translating an FRC plasma towards an injected ice pellet. Experiments¹⁰⁾ on the plasma production and the confinement have been carried out with small devices and obtained parameters of $s < 3.5$, $n_e = 10^{21}/\text{m}^3$, $T = 3 \text{ keV}$, and the energy confinement time $\tau_E = 400 \mu\text{sec}$. Those values should be compared to representative plasma parameters for D-³He fueled fusion reactors, i.e., $s = 10$, $T = 70\text{--}100 \text{ keV}$, $n_e = 7 \times 10^{20}/\text{m}^3$ and $\tau_E = 2 \text{ sec}$, respectively.

If the averaged ion gyration radius is much smaller than the plasma radius, i.e., $s \gg 1$, phenomena of an FRC plasma are governed by magneto-hydrodynamics and is tilt unstable¹¹⁾, since the toroidal current in an FRC plasma is strong enough to reverse the magnetic field at the axis of symmetry. In a D-³He burning plasma, however, certain energetic fusion produced protons escape through the plasma boundary and are lost directly along the open lines of force outside the plasma region, and others are trapped within the plasma region depending on their canonical angular momentum. The preferential trapping of the energetic fusion protons forms¹²⁾ a directed flow of energetic protons and it might stabilize^{13,14)} a plasma against the tilt modes, by the inertial effect which is seen in a betatron accelerator. This stabilization effect should be compared to that of tokamaks where the plasma is stabilized by an applied strong toroidal magnetic field, which brings necessarily a low beta-value of tokamak plasma.

Another important contribution of the directed energetic proton beam is driving¹²⁾ the current in an FRC, which is needed to sustain a configuration in a steady burning state. In the "ARTEMIS" 1 GW_e reactor design, for instance, 45 MA of current is estimated to be provided by the preferential trapping of the fusion protons and another 5 MA is due to a parallel injection of 1 MeV-5 A neutral beam particles.

Although an energetic fusion proton beam stabilizes macroscopic modes in an FRC, it may cause certain microscopic turbulences and consequently it brings anomalously large transports of plasma particles as well as the plasma energy. The transports observed in present experiments are about ten times larger than the classical transport, which are

estimated on the bases of the binary collisions between plasma particles. In a commercial fusion reactor, however, the anomaly factor to the classical transport should be less than several hundreds (an anomaly factor 200 is assumed in ARTEMIS design). For the case where the anomaly factor is much larger than several hundreds, certain stabilization methods so as to reduce the transports are needed to develop D-³He fueled FRC commercial fusion plants.

We have learned the characteristics of an FRC for D-³He fuels, which are summarized as follows:

- (1) An FRC plasma is confined by closed magnetic lines of force for good thermal insulation of the plasma,
- (2) an FRC plasma is surrounded by open lines of force for extracting fusion power carried by charged particles,
- (3) an FRC has no toroidal magnetic field and consequently has extremely high plasma beta-values, and
- (4) an FRC is so rigid that fueling is possible by translating FRC towards a slowly injected ice pellet.

Besides these intrinsic characteristics, a D-³He fueled FRC has following attractive characteristics relevant to achieve a commercial fusion plant:

- (5) A major portion of the plasma current is sustained by a directed proton beam which is formed automatically by the preferential trapping of the D-³He fusion protons, and
- (6) the energetic fusion proton beam stabilizes macroscopic modes in an FRC.

The detailed studies concerning these phenomena are needed to develop a D-³He fueled FRC reactor. Furthermore,

- (7) intensive investigations on microscopic turbulence and consequent anomalous transport due to the energetic particle beam are urgent.

4. D-³He Fueled FRC Reactor "ARTEMIS"

A conceptual design study of the D-³He fueled FRC fusion reactor "ARTEMIS" was carried out⁹⁾ for the purpose of examining its attractive characteristics and clarifying the critical issues for a commercial fusion reactor.

Fig. 5. A whole view of "ARTEMIS" composed of formation chamber, burning chamber, and direct energy converters

ARTEMIS consists of a formation chamber, a burning chamber, and a pair of direct energy converters (Fig. 5). An initial FRC plasma is produced by the conventional reverse-biased fast theta pinch method in the formation chamber and subsequently it is translated to the burning chamber. A combination of neutral deuterium beam injection (NBI), fueling, and a slow magnetic compression increases the volume, the temperature, and the number density of the plasma and evolves it to a D-³He burning state. A large fraction of the D-³He fusion

Table I. Plasma parameters at the phase.

	a	b	c
Plasma Radius (m)	0.7	1.0	1.12
Plasma Length (m)	4.8	14.8	17.0
Plasma temperature (keV)	1.0	1.0	87.5
Electron Density ($\times 10^{20} / \text{m}^3$)	4.1	0.62	6.6
Trapped Flux (Wb)	0.086	0.086	3.66
External Magnetic Field (T)	0.56	0.22	6.7 T
s-Value	5.9	2.7	9.2
Plasma β -Value	0.92	0.83	0.90

a: after the FRC formation at the formation chamber

b: after the translation to the burning chamber

c: steady burning state

energy is carried by charged particles along the lines of force and introduced to direct energy converters. Another fusion energy is carried by neutrons and photons to the first wall of the burning chamber and converted subsequently to electricity with heat exchanger and turbine generators.

The formation chamber is arranged symmetrically so as to produce FRC plasmas reliably even for a very low filling gas pressure. A fast rising theta-pinch discharge with a one turn voltage of 400 kV in a filling gas pressure of 0.05 Pa and bias field of 0.035 T produces an initial FRC plasma whose parameters are listed in Table I-a. Insulation for this high voltage is ensured by applying a 4-stage tandem structure of the pinch coils. Pulse SC coils of 1.87 MAT/coil at the formation chamber raises the magnetic field up to 1.26 T in a period of 50 msec. A large radius of 5 m is chosen for the pulse coils to reduce the coupling with the coaxial pinch coils of 2.1 m in radius, with an assist of a magnetic shielding plates.

The plasma is then translated to the burning chamber by an applied unbalanced cusp magnetic field. During the translation, the FRC conserves its particle numbers of respective species, the total energy, and the trapped flux. Plasma parameters obtained by this method at the burning chamber are listed in Table I-b.

A set of 10 super-conducting coils of 14.2 MAT/coil and radius of 3.5 m is installed at the burning chamber and supplies a magnetic field of 6.7 T. The required averaged current density is 30 A/mm² and the maximum stress on the coils is 300 MPa. In this chamber, the FRC plasma is heated by means of energetic neutral deuterium beam injections, whose maximum power is 100 MW. A slow magnetic compression is also applied. The injected particles form an ion beam current which plays a roll of the seed current to sustain or enhance the trapped magnetic flux in an FRC. Thus the plasma increases its volume, the density, and the temperature up to the values relevant to a D-³He burning plasma. Note that the ratio of the current carried by the energetic beam particles to the total plasma current is high enough to stabilize an FRC against macroscopic modes during the start up process. A set of obtained plasma parameters are tabulated in Table I-c.

In a D-³He burning FRC plasma, a current of 45 MA is attributed to the preferential trapping of fusion protons and 5 MA of external beam injections is supplemented to sustain an equilibrium in a steady burning state. A pellet of 1.8 mm³ volume consists of a cylindrical deuterium ice container and inner liquid helium-3 is injected every 0.09 sec. As a pellet locates near the center of the chamber, FRC plasma moves towards the pellet at a high speed more than 10⁴ m/sec with the aid of an applied cusp field and consequently engulfs it deeply inside the plasma. The particle flows in this D-³He steady burning FRC plasma are exhibited in Fig. 6, where the transports is assumed to be 206 times the classical one.

The bases of engineering employed in ARTEMIS design are conventional. Nevertheless,

Fig. 6. A particle flow chart of ARTEMIS.

Fig. 7. A power flow chart of D-³He FRC power reactor ARTEMIS: On the bases of high efficiency of the direct energy converters, an overall plant efficiency is as high as 62%.

development of efficient 1 MeV neutral beam injectors of 100 MW is needed for the start up phase of the FRC plasma in ARTEMIS. Other important engineering to be developed for a D-³He FRC reactor is the direct conversion of fusion power carried by charged particles into electricity. For the thermal component of a plasma, a "Venetian blind type" generator¹⁵⁾ (VBDEC) might be applicable. For 14.7 MeV fusion protons, however, the energy is too high to make use of an electrostatic direct energy converter. The concept of a "traveling wave direct energy converter"¹⁶⁾ (TWDEC) is developed based on the principle of a "Linac"¹⁷⁾.

The power flow chart of D-³He fueled FRC power reactor ARTEMIS is exhibited in Fig. 7. An efficiency of 36% is assumed for the conversion of heat energy to electricity. Because of high efficiencies of direct energy converters, the overall plant efficiency is estimated as high as 62%. The principal parameters of the reactor are shown in Table II. Since the device consists of straight tubes forming a linear geometry, it is easy to disjoint for maintenance. The 14 MeV neutron load of 0.26 MW/m² on the first wall enables the life of the first wall and structural materials to be permanent during the reactor life (> 40 years). Because of a low 14 MeV neutron flux and no breeding blanket, the safety of the reactor is inherent.

Table II. Principal parameters of D-³He fueled FRC fusion reactor ARTEMIS.

Fusion Plasma		
Volume	($r_s=1.12\text{m}$, $l_s=17\text{m}$)	67m ³
Fuels :	³ He and D	Density Ratio = 1 : 2
Averaged Electron Density		$6.6 \cdot 10^{20}/\text{m}^3$
Temperature		875 keV
β -Value		0.90
Plasma Chamber		
Formation Chamber	($r=1.8\text{m}$, $l=15\text{m}$, $t=0.15\text{m}$)	Alumina Tube
Burning Chamber	($r=2.0\text{m}$, $l=25\text{m}$, $t=0.05\text{m}$)	Ferritic Steel
Heat Load on the First Wall:		1.7 MW/m ²
14 MeV Neutron Load on the First Wall :		0.26 MW/m ²
Energy Conversion Chamber:	($r=10\text{m}$, $L=50\text{m}$, $t=0.05\text{m}$)	316 SA Tube
Magnetic Coils		
Pinch Coils :	$r=2\text{m}$, $L=10\text{m}$, 4-Stage Tandem Cu-Coils, $L_c=1.6\mu\text{H}$	
Pulse Coils :	$r=5\text{m}$, NbTi/Cu/CuNi Cable, 200T/sec, 4T, 1.87MAT*8	
Slow Coils :	$r=3\text{m}$, NbTi/Cu/CuNi, 7T, 14.2MAT*10	
Heating and Current Drive : NBI		
Start Up :	Max.1400keV, 100MW, D ⁰ Injection	
Steady Burning :	1000keV, 5MW, D ⁰ Injection	
Fueling : Packmann Method.		Liq. ³ He in an Ice D-Vessel
Deuterium :	56.4kg/year	
Helium-3 :	38.0kg/year	

Table III. Cost of electricity from ARTEMIS.

Capital Cost	146.0 M\$/y
Operation and Maintenance	34.6 M\$/y
Fuel Cost	8.0 M\$/y
Total Cost	188.6 M\$/y
Cost of Electricity = 28.7 mills/kWh (Load Factor 0.75)	

On the bases of the ESECOM study¹⁸⁾, the cost of electricity (COE) from ARTEMIS design is estimated as 28.7 mills/kWh, whose constitution is given in Table III. An averaged load factor of 0.75 is assumed. The estimated COE is cheaper than that from a present light water reactor, because the total weight of the reactor (approximately 3,300 tons) is 1/3 of a corresponding light water reactor. Although the volume of traveling wave direct energy converters is fairly large and it costs 12% of the reactor plant equipment, it produces 27% of the total electric power. It must be noted that the fuel cost (assumed cost of helium-3 obtained from the Lunar soil¹⁹⁾ is 0.2 M\$/kg) contributes only 4% and affects little on COE.

In the comprehensive ARTEMIS design, we have learned the following characteristics:

- (1) A complete physics scenario for a D-³He fueled FRC fusion reactor is available.
- (2) All the bases of engineering employed in ARTEMIS design are conventional and simple.
- (3) Owing to the intrinsic characteristics of D-³He fuels, radioactivity induced by 14 MeV neutrons decrease by the order 2 compared to D-T fuels and the safety of the system is inherent.
- (4) Because of the high beta-value of the fusion plasma, the reactor is compact and the estimated cost of electricity is cheaper than that from present light water reactors.

The gap between plasma parameters obtained in experiments and required parameters for commercial fusion reactors are, however, fairly large. Further, detailed physics concerning plasma stability and energy transport are still unclear. It is, therefore, urgent to initiate comprehensive investigations on the principles of ARTEMIS:

- (5) Stabilization, current drive, and enhanced transport due to the energetic particle beam. In parallel to the physics studies (5),
 - (6) development of 1 MeV neutral beam injectors, and
 - (7) development of the direct energy converters
- are inevitable to D-³He fueled FRC commercial reactors.

5. Summary

[Principle] :

By applying D-³He fuels to a fusion reactor, neutron yield decreases to below a percent of the total fusion power. Nevertheless, a very high temperature, an extremely high β value, and fairly large confinement parameters of the burning plasma are needed to utilize the fuels. An accessibility of high power direct energy converters is also required to obtain a high plant efficiency of a reactor. The intrinsic characteristics of an FRC appears to meet these requirement.

An FRC plasma is confined to closed magnetic lines of force for good plasma insulation and is surrounded with open lines of force for extracting fusion power carried by charged particles. Furthermore, an FRC has no toroidal magnetic field and consequently has extremely high plasma beta-values. Those intrinsic characteristics meet the requirements for economical aneutronic D-³He fusion reactors. By applying D-³He fuels to an FRC, the plasma current is sustained by a directed proton beam which is formed automatically by the preferential trapping of the D-³He fusion protons, and the energetic fusion proton beam stabilizes macroscopic modes in an FRC.

[Potential] :

A complete and consistent scenario of a D-³He fueled FRC reactor has been established. All the bases of engineering for this reactor are conventional. A reactor design shows the ecological and social acceptabilities of a D-³He fueled FRC reactor, because of its lower radioactivity and inherent safety. The estimated cost of electricity is cheaper than that from an economical light water reactor.

[Critical Issues and Risks] :

Although the physics scenario is available, certain uncertainty is left unresolved and therefore it may be urgent to study the details and establish the principles of a D-³He fueled FRC fusion reactor, i.e., detailed physics of driving the plasma current and stabilizing macroscopic modes in an FRC by means of a directed proton flow which is formed by the preferential trapping of the D-³He fusion protons. Studies on microscopic turbulences and related anomalous plasma transports are also the critical issues for developing high-efficiency aneutronic D-³He fusion reactors.

[Necessary Experiments] :

On the bases of the ARTEMIS design and experiments so far carried out, the next experiments on FRCs will be focused to proof of principles (POP) of the highly efficient D-³He fueled FRC fusion reactors. The physics scenario of the plasma production and the control is essentially the same as that of ARTEMIS. The plasma device for this experiment consists of ceramic formation chamber (3 m in length and 0.25 m in radius) and heating chamber (10 m in length and 0.6 m in radius) which is made of metal. A plasma current of 6.9 MA will be obtained with an external magnetic field of 1 T. The first 6 years will be spent in planning of the project, construction of the devices, and the preliminary experiments. Developments of a 1.2 MeV-19 A neutral deuterium beam source and direct energy converters will be in parallel. The full power operations for the POP experiments will be carried out for the following 3 years. The estimated total capital cost of this program will be about 50 M\$.

Since the bases of engineering for this highly efficient D-³He fueled FRC fusion reactor are conventional, the steps of the developments to commercial fusion reactors will be quite different from that for light water reactors or D-T reactors, i.e., engineering feasibility will be proven in parallel to the POP experiment and no needs to demonstrate the economical feasibility because of its extremely cheap estimated COE. Thus the POP experiment will be

followed by the construction of a prototype fusion reactor for the first decade of the 21st century.

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