Progress in Fusion-Driven Transmutation Research in China

Yican WU
Institute of Plasma Physics, Chinese Academy of Sciences
P.O. Box 1126, Hefei, Anhui, 230031, China
E-mail: ycwu@mail.ipp.ac.cn
Fax: +86 551 5591310

1. Introduction

Although the recent experiments and associated theoretical studies of fusion energy development have proven the feasibility of fusion power, it's commonly realized that it needs hard work before pure fusion energy could commercially and economically utilized. On the other hand, the fission nuclear industry has been falling on hard times recently since so far there has been no conclusion about how to deal with the long-lived wastes produced from the nuclear spent fuel and about how to solve the shortage of natural uranium ore in addition to nuclear safety and proliferation. It's a natural way to develop fusion-fission hybrid reactors including fuel producing reactors and waste transmuting reactors as an alternate strategy to speed up the time for producing energy since a hybrid reactor as a subcritical system can operate with lower fusion energy gain ratios Q, therefore the design of the fusion core for a hybrid system is easier than for a pure fusion reactor.

The fusion-fission hybrid concept dates back to the earliest days of the fusion project when it was recognized that using fusion neutrons to breed nuclear fuel would vastly increase the energy from fusion plant. It appears to receive almost no attention since the mid 80's in the world, except in China who has given very serious consideration and has strong hybrid reactor activities since 1986 in the framework of the National Hi'Tech Program supported by the State Science and Technology Commission (SSTC) of China.

In 1990 the scientists at the Institute of Plasma Physics -ASIPP (later in 1995 at the Southwest Institute of Physics - SWIP) started to reassess the feasibility of transmutation of wastes using hybrid reactors in the framework of the National Hi'Tech Program[1-5]. This work had been sponsored further by the National Natural Science Foundation of China (NSFC) with the Project "Study on Disposal of Long-lived Radioactive Wastes" during 1994-1996 [6].

The first phase of the Hi'Tech Program supported by the SSTC had been finished by the end of 2000 and the study on Fusion-Driven Subcritical Clear Nuclear Energy System for waste transmutation and fuel production is being performed in the framework of the Knowledge Innovation Program supported by the Chinese Academy of Sciences (CAS).

In this paper, the overview on conceptual design activities of fusion-fission hybrid reactors to supply nuclear fuel for fission power plants is presented in Section 2, where besides the conceptual design, plasma experiment and related R&D, the current status and consumption prediction of energy resource are briefly included. The activities on transmutation-related fusion core conceptual research, mainly on spherical tokamak conceptual study, are given in Section 3 and the research activities on transmutation blanket concepts are given in Section 4. Finally, the future prospect for transmutation systems is presented in Section 5.

2. Overview on Conceptual Design Activities of Fusion-Fission Hybrid Reactors

A general subcritical fusion-fission hybrid system has many attractive features such as having the fusion neutrons improve the overall neutron balance of the fission blanket system, having the fission blanket improve the overall energy balance of the fusion driver, having no critical accident risk and reducing real proliferation dangers, benefiting both fusion energy development by providing a test-bed for the development of fusion reactors and giving experience with a large-scale pure fusion device and fission nuclear industry development by solving the problems of long-lived waste disposal and fuel supply limitation etc.[7]. China has strong fusion-fission hybrid study activities at ASIPP and at SWIP since 1986. Actually, in 1980-85 they did physics concepts studies, in 1986-95 a detailed conceptual design had been finished, in 1996-2000, an outlined engineering design has been performed. The fusion-fission

hybrid system is considered to be a step towards pure fusion.
During the period of the hybrid reactor program, China has built and operated two middle-sized tokamaks (HT-7 and HL-1/1M)[8,9] and now is building another two tokamaks (HT-7U at ASIPP and HL-2A at SWIP)[10,11]. Their main parameters are listed in Table 1. The HT-7 and HL-2A have been built based on the modification of the former Russian superconducting tokamak T-7 and the former German normal conducting tokamak ASDEX with the elongated cross section. The superconducting tokamak HT-7U and the normal conducting tokamak HL-1/1M have been designed and built by Chinese scientists. Long pulse operation (the designed maximum pulse length is 1000 seconds) will be studied on the HT-7U tokamak with D-D discharge.

Table 1 Main Parameters of Some Tokamak Devices in China

Tokamak	HT-7	HT-7U	HL-1M	HL-2A
Major radius R[m]	1.22	1.7	1.02	1.64
Minor radius a[m]	0.3	0.4/0.8	0.26	0.50
Elongation κ		2		1.6-1.8
Aspect ratio R/a	4.1	4.5	4.0	3,3
Toroidal field B_T[T]	2.5	3.5	3.0	3-3.5
Plasma current Ip[MA]	0.40	1.0	0.35	0.8-1.0
Discharge pulse length t_d [S]	1-5	~1000	1.0	5-10

Besides plasma experiments, a series of R&D for blanket engineering have been performed in China such as neutronics integral experiments to test tritium breeding, neutron breeding and multiplication, nuclear fuel breeding and neutron shielding[12-14], tritium production experiment using a fission reactor at SWINPC (Southwest Institute of Nuclear Physics and Chemistry)[15], fusion-hybrid related material studies (structure materials, tritium breeding materials, tritium permeation barrier materials, plasma facing materials have been involved) at CIAE(Chinese Institute of Atomic Energy), SWIP and IMF(Institute of Modern Physics)/CAS, and liquid metal loop experiments etc. at SWIP[16].

3. Transmutation-related Fusion Core Study

The fusion core studies in China have included the conceptual design on the normal tokamak experimental reactor FEB and the conceptual optimization on spherical tokamak in addition to the continuous experimental efforts on tokamak devices. The FEB core design study jointly by the ASIPP and SWIP Joint Design Team have covered numerical simulation and analysis on plasma heating, current drive, energetic _-particle confinement, fueling and ash exhausting, plasma burning control, plasma evolution process, diverter design with gas puffing and electromagnetic plug, sensitivity of plasma parameters to uncertainty etc. A set of optimized design parameters are presented in Table 2 [17].

Table 2 Main parameters of the FEB core

Major radius R[m]	4.0
Minor radius a[m]	1.0
Plasma current Ip[MA]	5.7
Toroidal field B_t[T]	5.2
Average density $<n_e>[10^{20}m^{-3}]$	1.1
Average temperature <T>[kev]	10
Plasma volume[m^3]	134
Fusion power P_{fu}[MW]	143
Auxiliary power P_{aux} [MW]	50
Neutron wall loading P_w[MWm^{-2}]	0.43
DT neutron rate(n/sec)	$1.1*10^{19}$
Power gain Q	~3
Operation availability	50%

To seek for new and efficient way to realize a volumetric neutron source, the spherical tokamak concept has been studied in China. Spherical or low aspect ratio tokamaks (ST) with aspect ratio (A) in the range of 1.2~2.0 offer the possibilities of compact volumetric fusion neutron sources as well as fusion reactors requiring relatively low external fields [18,19]. Furthermore, this kind of compact tokamak might offer some attractive advantages such as a cost-effective, high performance (high stable beta in the first stability boundary) plasma regime[20,21]. One of the attractive potential applications is to transmute long-lived actinides and fission products produced by fission power plants. Recent progress in spherical tokamak experiments and associated theoretical studies as well as contribution to the mainstream tokamak program [22-26] provided added impetus to the verification of the physics in this regime and the assessment of its reactor prospects.

In ASIPP, the conceptual study on spherical tokamak has been oriented on the level of volumetric neutron source for the purpose of nuclear waste transmutation. The optimized core parameters of the spherical tokamak neutron source by L Qiu et al. are listed in Table 3[27].

Table 3. The optimized core parameters of spherical tokamak volumetric neutron source

Total fusion power P_f [GW]	0.1
Major radius a[m]	1.4
Neutron wall loading P_w[MWm^{-2}]	1
Plasma current Ip[MA]	9.2
Center post current [MA]	9.0
Aspect ratio A	1.4
Elongation κ	2.5
Triangularity δ	0.45
β_N	6.5
β_t %	35
Poloidal β_p[%]	0.95
Bootstrap current fraction [%]	0.81
Toroidal field B_t[T]	2.5
Plasma edge q	5.5
Average density $<n_e>[10^{20}m^{-3}]$	1.1
Average temperature <T>[keV]	9.5
Plasma volume[m^3]	50
Auxiliary power P_{aux} [MW]	19

A design with an aspect ratio near the lower limit (due to limited space) requires an unshielded center conductor post (CCP) as part of the toroidal field coil (TFC) circuit. The fully exposed CCP will receive severe neutron damage, resistive and nuclear heating power, which is one of the key components and requires replacement at regular intervals. The analysis results for the CCP considering neutron radiation effects such as radiation damage, transmutation, nuclear and resistive heat removal, induced radioactivity and blanket tritium breeding ratio etc in a spherical tokamak reactor comparing with those estimated for the first wall (FW) of regular tokamak reactors (RT) have been carried out to show if the technical requirements are comparable [28]. The analyses have shown that the severity of neutron radiation damage and transmutation in the CCP is comparable with that estimated for the first wall of conventional tokamak reactors. Thus, radiation damage, transmutation effects and other relevant problems of the CCP need to be studied further if a design with a high neutron wall loading is adopted.

Besides design of conventional CCP conceptual study, novel concepts on liquid metal CCP are proposed and studied instead of the conventional CCP made of copper alloy. The new concepts covered the ones with liquid metal as coolant, or both coolant and electric current carrying medium. Comparing with the conventional concept using copper or copper alloy, the novel concepts have the following potential advantages: [29,30] such as less transmutation wastes produced by regular replacement due to the application of low induced activity structure material and the reduction of amount of required regularly replaceable material, almost no electric conductivity change after a long time operation due to application of liquid metal as current transferring medium, easy removal of resistive and nuclear heat due to application of liquid metal as heat transfer medium, tolerable neutron structure damage since various materials may be selected for the structure, the service lifetime of CCP could be long enough, enhancement in tritium breeding ratio due to application of Li element in liquid metal etc. Those novel concepts have also left a lot of challenging engineering problems to be solved further.

4. Transmutation-related Blanket Study

The blanket system is one of the most important components of a tranmutation reactor because it has a major impact on both the economics and safety of the system. Besides breeding tritium for the fusion fuel cycle, efficient multiplication and effective usage of neutrons in the transmutation blanket are emphasized for all the designs by adding suitable neutron multiplication materials (mainly the materials such as beryllium, lead with high (n,2n) threshold reaction cross section and the heavy metal material with high fission cross section) and arranging the zone builds to form suitable neutron energy spectra for the effective usage of neutrons.

To perform the function of transmuting the HLW(high Level wastes) from fission power plants in fusion hybrid blankets, a lot of design research had been done in USA in the 70's [31-34] and in China in the 90's [1-3,7]. The HLW resulting from reprocessing contains both actinides and fission products. Since all actinide isotopes are radioactive, the (n,_) and (n,2n) reactions are not effective transmutation processes for managing these wastes. The most effective transmutation process for the actinides is fission, and, therefore, this leaves the fission product wastes as the primary candidates for transmutation in the fusion device. The transmutation of the very long-lived fission products such as ^{129}I, ^{135}Cs and ^{99}Tc etc. could be effectively transmuted by fusion neutrons. The previous studies in USA[32,33] had shown that a sharp reduction in the short-term toxicity of the fission product wastes could not be accomplished due to the small capture cross sections of ^{90}Sr and ^{137}Cs and limitations on the neutron flux via the transmutation reactions in the blankets of pure fusion reactors. Due to the limitations on neutron flux level (limited by achievable fusion neutron wall loading), the blankets for transmutation of fission products must be highly moderated in order efficiently to utilize the dominant (n,_) transmutation reaction. Therefore, the blankets must contain good neutron moderating materials with low thermal neutron absorbing cross sections such as heavy water, graphite etc.

Considering the level of neutron wall loading based on achievable fusion plasma technology and material technology and simultaneously keeping the blankets reasonably subcritical for the reason of safety margin and heat power density limitation, the blankets for transmutation of actinides must be designed to have hard neutron spectra to effectively utilize the fast fission reaction of actinides at above the fission threshold energy.

In the 1990's, China has performed a lot of studies on transmutation of long-lived nuclides in the blankets of hybrid reactors besides on breeding nuclear fuel using hybrid reactors. Their studies have covered various blanket concepts:

(1) Thermal fission blanket concept with plutonium-239 fissile neutron multiplication material for transmutation of fission products. The studies have shown that the effective transmutation for all fission products could be accomplished in the highly moderated blankets of hybrid reactors in which the highly efficient neutron multiplier (fissile plutonium-239 or uranium-233) is added [1-2].

(2) Hard neutron spectrum blanket concepts for transmutation of actinides. The helium-cooled nitride particle fuel of actnides or the liquid metal (LiPb eutectic or sodium) cooled metallic alloy (e.g. Y/Zr alloy of actinides) fuel is used. Metallic fuel or nitride fuel is preferred to oxide fuel because it may provide harder neutron spectrum or it allows to implement a compact fuel sycle concept based on pyrochemical process, and liquid metal cooled fuel or particle fuel allows higher power density because of high heat transfer capacity[35].

(3) Thermal neutron spectrum blanket concept for transmutation of actinides. The heavy water is a good coolant and a good neutron moderating material. In fuel, fissile plutonium-239 is loaded as neutron multiplier and reactivity control material (controlling Keff of the system to make the blanket subcritical and power-stable)[36].

(4) Helium and LiPb eutectic dual cooled fast fission blanket concept simultaneously for transmutation of actinides and long-lived fission products. This blanket consists of three actinide transmutation zones, in which actinides and plutonium with different concentrations to flatten

power peak, and one fission product transmutation zone adjacent to actinide transmutation zones. The fission product transmutation and the first wall are cooled with helium gas, and the actinide transmutation zones are cooled with LiPb eutectic. Actinides mixed with plutonium could be made into one kind of samll fuel sphere coated by SiC which is compatible with liquid LiPb well. Simultaneously LiPB could be used as the tritium breeder (with Li) and the neutron breeder (with Pb). Graphite, an excellent neutron moderator and refeclor, is loaded in the fission product transmutation zone[37].

(5) Multi-function thorium-uranium fuel cycle blanket concept. The minor actinide is initially loaded into the blanket in the form of pebble beds in the inner zone closed to the first wall. Tritium breeding zone with Li2O is arranged between the actinide transmutation zone, in which minor actinides(NpAmCm) mixed with uranium-233 are loaded, and fissile fuel uranium-233 breeding zone with natural thorium-232. The long-term toxic fission products (^{135}Cs, ^{129}I and ^{99}Tc) can be efficiently transmuted in the outer zone with good neutron moderator. This blanket could be used to achieve several functions: HLW transmutation, fissile material breeding, tritium self-sustaining and energy amplification. Finally the following energy amplification can be gained:

$M=E_{fission}/E_{fusion}=k_{eff}/[\_(1-k_{eff})]$, where M is the energy amplification factor, Efission is the energy released by a fission event (eg. ~200MeV), Efusion is the energy released by a fusion event (e.g. 14MeV for DT fusion), keff is the effective multiplication factor (subcritical factor), and _ is the neutron number produced by a fission event [38].

In their studied concepts, fissile plutonium-239 and uranium-233 have been introduced into the blankets for neutron multiplication and energy balance adjustment. Thus the requirement for fusion driver technology could be much more easily satisfied, that is, the plasma core parameters and fusion technology requirements are far less stringent. The effective transmutation of long-lived waste nuclides could be achieved based on the requirement for relatively low neutron wall loadings of 0.2~1.0 MW/m^2 which are between the levels of the one achieved in the tokamak device JET and the one in the ITER engineering design.

5. Future Prospect of Fusion-Driven Transmutation Systems

To meet the ever increasing energy requirement due to improvements of the economy and living stand of Chinese people, the situation of the energy supply will become more and more serious. It is predicted to need 1200-1500 GWe power in 2050 with a population of 1.5 billions. Even if nuclear power is ~10% in the electricity supply in the middle of this century, China will need more than 100 standard nuclear power plants, which will consume a large scale of fissile nuclear fuel and result in the accumulation of a large amount of long-lived nuclear radioactive wastes. If we assume a 30% fraction of electric power is contributed by nuclear energy by the middle of this century, the capacity of nuclear electricity will reach 400GWe. The study on nuclear fuel cycle has shown that there will be no possibility to achieve that goal without the contribution of fusion-fission hybrid energy systems based on the U-Pu fuel cycle with the foreseeable uranium ore in China, as shown in Fig.1[39].

On another hand, we have to go a long way to realize commercial utilization of pure fusion energy although great progress in plasma experiments and associated theoretical studies and R&D have recently been achieved. However, a fusion-fission hybrid system could reduce the requirement of fusion plasma technology and engineering since it needs a lower parameter fusion core in addition to its potential to dispose of fission industry wastes.

The attractiveness of a transmutation-based waste management system depends on a number of factors. These include neutronic, material, and chemical separation considerations, as well as the design of the transmutation system.

The feasibility studies have shown that the conventional tokamak physics database (including the >10MW level D-T operating experience in TFTR (USA) and JET (EU) and the existing technology which has been developed and tested in the $750M US$ ITER R&D program) is sufficient to allow the design and construction of the neutron sources for waste transmutation and fuel breeding with modest annual neutron fluence capability although some challenging problems will probably be encountered. The advanced tokamak physics database that is rapidly accumulating is extending the design basis for continuous operation, reduced cost, and annual neutron fluence accumulation. A substantial advance in the database for long pulse operation will be supplied by the superconducting tokamaks KSTAR(Korea)[40] and HT-7U (China)[10]. A prototype tokamak experimental reactor could be performed almost at the level (the neutron wall loading of ~0.5 MW/m2 and the availability of ~50%) of ITER-RC[41].

The definition and conceptual design of the next experimental device after HT-7U are being performed at ASIPP. If we want to build commercial transmutation hybrid reactor around 2035, the Eng. Design Activities for the experimental transmutation reactor and R & D of key components should be performed in China before 2010 in order to build an experimental reactor within the period of 2010-2020 and to build Demo reactor 2020-2030.

References

1. Y.C. Wu, Research on Transmutation of High Level Wastes Using Fusion-Fission Hybrid Reactors, Ph.D thesis, Institute of Plasma Physics, Chinese Academy of Sciences (1992).
2. Lijian Qiu, Yican Wu, Qiang Xu, Qunying Huang, Transmutation of ^{90}Sr Using Fusion-Fission Hybrid Reactors, Proc. of the 14th IAEA Inter. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, IAEA-CN-56/G-2-4, Vol.3, p.391 - 398, Wuerzburg, Germany, Sept.30 - Oct.7, 1992 .
2. Y.C. Wu, Y.W. Yang, L.J. Qiu, Y. Wu, G.S. Luan, Q. Xu, Z.J. Guo, B.J. Xiao, Waste Transmutation and Nuclear Generation Using a Small Tokamak Fusion-Fission Hybrid Reactor, Proc. of the 7th Inter. Conf. on Emerging Nuclear Energy Systems, p.197 - 200, Makuhari, Chiba, Japan, Sept.20 - 24, 1993.
3. L.J. Qiu, Y.W. Yang, Y.C. Wu, G.S. Luan, B.J. Xiao, Z.J. Guo, Q. Xu, P. Duan, Y.Wu, L.L. Liu, Q.Y. Huang, A Compact Tokamak Transmutation Reactor for Treatment of High Level Wastes (HLW), paper presented at the 15th IAEA Inter. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Seville, Spain, Sep. 26 - Oct. 1, 1994.
4. K.M.Feng, J.H.Huang, Transmutation Calculation of ^{237}Np with a Fusion Reactor, J. of Fusion Engineering and Design, 29 (1995) 64-68.
5. K.M.Feng, G.Hu, Transmutation of Nuclear Wastes in a Fusion Breeder, present at International Symposium on Fusion Nuclear Technology, Aril 6-11,1997, Tokyo, Japan.
6. “Study on Disposal of Long-lived Radioactive Wastes”, Project of National Natural Science Foundation of China, Contract No. 19385004 (1994-1996).Yican Wu, Fusion Neutron Source Driven Sub-critical Nuclear Energy System --- A Way for Early Application of Fusion Technology, presented at the 6th Japan-China Symposium on Materials for Advanced Energy Systems and Fission & Fusion Engineering, Kyushu University, Japan, Dec.4-6, 2000.J. Li, B.N. Wan, J.S. Mao and HT-7 Team, Experimental progress on HT-7 superconducting tokamak in 1998, paper presented at the 26th EPS Conf. on Controlled Fusion and Plasma Physics, 14-18 June 1999, Maastricht, The Netherlands.Peide Weng et al., "The engineering design of HT-7U Tokamak", paper IAEA-CN-77/FTP2/19 presented at the 18th IAEA Fusion Energy Conference, Sorrento, Italy, 4 to 10 October 2000. paper IAEA-CN-77/OV5/4 presented at the 18th IAEA Fusion Energy Conference, Sorrento, Italy, 4 to 10 October 2000.Yican Wu, Yixue Chen, Ulrich Fischer, Yuan Chen, Li An, Integral Data Test of FENDL-2 Fusion Nuclear Data Library with Neutroncs Shiled Experiments, Journal of Nuclear Science and Technology, supplement 1 (March 2000).

15.

16. Fusion Engineering and Design 49-50 (2000) 477-482.
17. J.H. Huang, L.J. Qiu, Joint Design Team of SWIP and ASIPP, “Detailed Conceptual Design of the Fusion Experimental Breeder, Fusion Engineering and Design 41 (1998) 597-603.
18. Y-K.M. PENG and D. J. STRICKLER, Features of Spherical Torus Plasma, Nucl. Fusion 26, 769(1986).
19. Y-K.M. PENG and J. B. HICKS, paper presented at the Symposium on Fusion Technology, London, 1990.
20. L.J. QIU, Z.J. GUO, Y.C. WU et. al., Some Key Issues of Compact Tokamak Reactor Design for Volumetric Neutron Source (VNS) Application, paper presented at the 3rd Sino-Japanese Symposium on Materials for Advanced Energy Systems and Fission and Fusion Engineering, Chengdu, PR China, Oct.30 - Nov.3, 1995.
21. D.C. ROBINSON et. al., Paper CN-60/F-I-3 (1) presented at the 15th IAEA Fusion Energy Conference, Seville, Spain, Sept.26-Oct.1, 1994.

22. D.C. ROBINSON, R.BUTTERY and I. COOK et. al., The Way Forward for the Spherical Tokamak, paper presented at the 12th Topical Meeting on the Technology of Fusion Energy, June 16-20, 1996, Reno, Nevada.
23. R.D. STAMBAUGH et. al., The Spherical Tokamak Path to Fusion Power, Fusion Technology, 33 , 1 (1998).
24. JET TEAM, Plasma Physics Cont. Nucl. Fusion Res. 1, 41 (1989).
25. E. A. LAZARUS et. al., Cont. Fusion and Plasma Heating, Vol. 14B, Part I (EPS, 1990) 427.
26. M KIKUCHI et. al., "Bootstrap Current during Perpendicular Neutrol Injection in JT60," Nucl. Fusion 30, 343 (1990).
27. L.J. Qiu, Y.C. Wu, B.Wu, X.P. Liu, Y.P. Chen, W.N. Xu, Q.Y. Huang, Advanced Study of Tokamak Transmutaton System, paper IAEA-CN-77/FTP2/09 presented at the 18th IAEA Fusion Energy Conference, Sorrento, Italy, 4 to 10 October 2000.
28. Yican Wu , Bingjia Xiao, Qunying Huang, Lijian Qiu, Neutron Radiation Effects of the Center Conductor Post in a Spherical Tokamak Reactor, Fusion Technology, Vol.35, No.1, pp.1-7, 1999.
29. Yican Wu, Lijian Qiu, Yixue Chen, Conceptual Study on Liquid Metal Center Conductor Post in a Spherical Tokamak Reactors, Fusion Engineering and Design 51-52 (2000) 395-399.
30. J. Yu, Y. Wu, J. Sha, Q. Huang, Y. Ke, Neutron Radiation Effects of the Center Conductor Post in a Spherical Tokamak Reactor, paper to be presented at the Inter. Conf. of Fusion Reactor Materials, Baden-Baden, Germany, Oct. 2001.
31. Ronald P. Rose et al., "Fusion-Driven Actinide Burner Design Study", Research Project 473-1, Final Report, EPRI ER-451 (1976).
32. T.A. Parish and E.Linn Draoer, Jr., Determination of Procedures for Transmutation of Fission Product Wastes by Fusion Neutrons, Final Report on EPRI Research Contract 474-2, Nuclear Reactor Laboratory, University of Texas (1976).
33. T.A. Parish, R.W. Davison, Reduction in the Toxicity of Fission Product Wastes through Transmutation with Deuterium-Tritium Fusion Neutrons, Nuclear Technology, Vol.47, pp.324-342 (1980).B.F. Bourque, K.R. Schultz, Fusion Applications and Market Evaluation (FAME) Study, Rep. GA-A-18658, General Atomics, San Diego, CA; Rep. UCRL-21073, University of California, CA (1998).
35. Y.C. Wu, L.J. Qiu, Y.X. Chen, et al., ,Waste Transmutation and Energy Production in Spherical Tokamak Hybrid Reactor, presented at the 20th Symposium on Fusion Technology (SOFT), Marseille, France, Sept.7-11, 1998.
36. Y.C. Wu, L.J. Qiu, Waste Transmutation and Nuclear Energy Generation Using a Tokamak Fusion-Fission Hybrid Reactor, Proc. of the 2nd Japan/China Symposium on Materials for Advanced Energy Systems and Fission and Fusion Engineering, University of Tokyo, Tokyo, Japan, June 4 - 12, 1994.
37. Yixue Chen, Yican Wu, Conceptual Study on High Performance Blanket in a Spherical Tokamak Fusion-Driven Transmuter, Fusion Engineering and Design 49-50 (2000) 507-512.
38. L.J. Qiu, Y.C. Wu, B.J. Xiao, et al., "A Low Aspect Ratio Tokamak Fusion Neutron Driven Transmutation System", Nuclear Fusion, Vol.40, No.3y ,pp.629-633 (2000).
39. Lijian Qiu, Chenggang Xia, Qunying Huang, "Discusion on the Development of Nuclear Energy in the Next Century Based on Fuel Cycle Analysis and Economic Assessment", Chinese J. of Nucl. Sci. Eng., Vol.10, No.4 (1990).
40. G.S. Lee et al., "Design and Construction of the KSTAR Tokamak", paper IAEA-CN-77/OV7/1 presented at the 18th IAEA Fusion Energy Conference, Sorrento, Italy, 4 to 10 October 2000.
41. "Study of Options for the Reduced Technical Objectives/Reduced Cost (RTO/RC) ITER", report presented at the ITER Council Meeting No.15, March 10-11, 1999. Also see "ITER-FEAT Outline Design Report", ITER Meeting, Tokyo, January