Fusion-Fission Hybrids Driven Research in China

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1. Characteristics of Fusion-Fission Hybrids

Although the recent experiments and associated theoretical studies of fusion energy development have demonstrated the feasibility of fusion power, there will still be a long way to realize fusion energy application commercially and economically. 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 is a natural way to develop fusion-fission hybrid reactors as an alternative strategy to speed up the time for producing energy since the fusion-fission hybrid systems/reactors have the potential attractiveness of good safety performance and plenty of fuel and easing the requirement of fusion plasma technology (with a low fusion gain Q) and plasma-facing material technology [1-3] (with a low neutron wall loading). As an intermediate step between fission energy application and fusion energy application, the fusion-fission hybrid reactors can be further utilized as a neutron source for R&D of fusion reactor itself [4].

2. Design Activities of Fusion-Fission Hybrids

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 fissile nuclear fuel would vastly increase the energy from the fusion plant. It appears to receive almost no attention since the mid 80's in the world, except in China which has given very serious consideration and had strong hybrid reactor activities.

Along with the ongoing efforts to establish fusion as an energy source, there has been a renewed interest in fusion neutron source applications. In addition to fundamental neutronics research, fusion research and development (R&D) activities are becoming of interest in nuclear fission power development. Indeed, for nuclear power development to become sustainable as a long-term energy option, innovative fuel cycle and reactor technologies will have to be developed to solve the problems of resource utilization and long-lived radioactive waste management.

The fusion-fission hybrid system is considered to be an intermidiate step toward pure fusion. A series of fusion-fission hybrid studies has been made in China [5-6]. Since 1986, the hybrid reactors have been given serious consideration in China as a national program. Fusion-fission hybrid study activities were developed at the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) and at the Southwestern Institute of Physics (SWIP) in the framework of the National High-Tech R&D Program ("863" Program) supported by the State Science and Technology Commission (SSTC) of China. Previously, in 1980-1985, physics conceptual studies were conducted, in 1986-1995, a detailed conceptual design of the Fusion Experimental Breeder (FEB) was completed, and in 1996-2000, an outline of the engineering design had been proposed. The main purpose of FEB is fissile fuel breeding. Under the tritium self-sufficient condition, the annual fuel breeding capability is about 100 kg.

In addition, designs of the fusion-driven subcritical system-a multipurpose experimental hybrid reactor that could perform many functions such as breeding nuclear fuel, transmuting long-lived wastes, producing tritium for fusion fuel cycles as an alternate approach to utilize fusion energy technology based on previous hybrid reactor studies in China are being conducted.

Since 2000, the study on Fusion-Driven Subcritical Clear Nuclear Energy System and the Multi-functional Blanket 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 1999-2002, the spherical tokamak concept has been studied in China with a view of using it as a volumetric neutron source [7-8]. Spherical or low aspect ratio tokamaks (ST) with aspect ratio in the range of 1.2~2.0 offer the possibility to develop a compact volumetric fusion neutron source requiring relatively low external fields. Furthermore, the low aspect ratio tokamak might offer some attractive advantages such as a cost-effective, high performance (such as high stable beta in the first stability regime) plasma regime. 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 provided added impetus to the verification of the physics in this regime and the assessment of its reactor prospects.

ASIPP made a conceptual design study of a spherical tokamak as a volumetric neutron source for nuclear waste transmutation. Tight aspect ratio tokamaks present a series of problems due to space limitations. A design with an aspect ratio near the lower limit requires an unshielded center conductor post (CCP). The fully exposed CCP will suffer severe neutron and heat damage, requiring periodic replacement. Studies have been carried out to see whether the technical requirements are comparable to conventional tokamaks. The studies have shown that the level of neutron damage is comparable to that estimated for the first wall of conventional tokamak reactors [9-10]. 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.

In addition to CCP made of copper alloy, novel concepts of liquid metal CCP have been studied. The studies included the use of liquid metal as both coolant and electric current carrying medium. The studies showed that liquid metals have potential advantages such as less transmutation waste produced by regular replacement, almost no electric conductivity change after a long time of operation, easy removal of resistive and nuclear heat due to the use of liquid metal as heat transfer medium, tolerable neutron structural damage since special materials may be selected for the structure. The studies showed that the service lifetime of CCP could be sufficiently long. Nevertheless, many challenging engineering problems remain.

After 2002, the fusion-driven subcritical system (named FDS-I [11]) was previously proposed as an intermediate step toward the final application of fusion energy. A conceptual design of the FDS-I was presented, which consists of the fusion neutron driver with relatively easily-achieved plasma parameters, and the helium-gas/liquid lithium-lead Dual-cooled subcritical Waste Transmutation (DWT) blanket [12] used to transmute long-lived radioactive wastes and to generate energy on the basis of self-sustainable fission and fusion fuel cycle.

In 2003 the IAEA has initiated a Coordinated Research Project (CRP) on "Studies of Advanced Reactor Technology Options for Effective Incineration of Radioactive Waste" [13]. Sixteen institutions from 12 member states and one international organization participated in this CRP. The CRP concentrated on the assessment of the dynamic behaviour of various transmutation systems. The reactor systems investigated comprise critical reactors, subcritical accelerator driven systems with heavy liquid metal and gas cooling, critical molten salt systems and fusion-fission hybrid systems. The FDS team in ASIPP as the coordinator of domain VIII (fusion-fission hybrid system), undertook the second workshop in ASIPP. The steady state core configurations and transient/accident simulations were performed based on the fusion-driven subcritical system FDS-I.

Along with the achieved and ongoing efforts to establish fusion as an energy source, there is a renewed interest in fusion-fission hybrid reactors, especially based on the progress in the construction and operation of EAST in China and ITER. So in ASIPP, three types of fusion-fission hybrid reactor concepts, i.e. the energy multiplier named FDS-EM [14] with the goal of energy production, the fuel breeder named FDS-FB with the goal of fissile fuel breeding, waste transmuter named FDS-WT with the goal of transmutation of the long-lived nuclear wastes, have been proposed for the re-examination of feasibility, capability and safety & environmental potential of fission-fusion hybrid systems under the support of CAS [15]. Three types of fission blankets have been designed and assessed in conjunction with three types of plasma cores at a fusion power of 50MW, 150MW and 500MW, respectively. The preliminary analyses covering neutronics, thermal-hydraulics and thermo-mechanics, etc. show that performances of FDS-EM, FDS-FB and FDS-WT were highly feasible and attractive although each of them has its own features.

Three types of hybrid concepts i.e. FDS-EM, FDS-FB and FDS-WT are conceptually designed and re-evaluated based on available or very limited extrapolated fusion (i.e. a fusion power of 50~500MW) and fission technologies (i.e. Water-cooled PWR or He-cooled HTGR technologies).

The conceptual design of FDS-EM, FDS-FB and FDS-WT, which consists of fusion plasma core parameter design and optimization, fission blanket and fuel cycle, and reference blanket module design, has been presented. And the preliminary performance analyses covering neutronics, thermal-hydraulics and thermo-mechanics have been carried out. FDS-EM / FDS-FB / FDS-WT is a practical path to the early fusion application for energy production / fissile fuel breeding / nuclear waste transmutation in a sub-critical reactor, which is based on available fusion technologies (the level extrapolated from the operation of the EAST tokamak) and mature fission reactor technologies such as PWR (Pressurized Water Reactor) or helium-cooled HTGR technologies..

The neutonics analyses showed the maximum energy multiplication factor M (M, which is defined as the ratio of fission power to the source neutron power (80% of fusion power in the deuterium-tritium fusion fuel cycle)) can be ~130, the maximum fissile fuel breeding ratio BSR (BSR, which is defined as the ratio of the fissile plutonium mass bred by FDS-FB to the fissile plutonium mass depleted by a referred PWR (3000MWth PWR with fuel burned to 33 GW.D/T) per year))can be ~10, the maximum waste transmutation ratio TSR (TSR, which is defined as the ratio of the waste mass transmuted by FDS-WT to the waste mass produced by a referred PWR per year) can be ~15, depending on specific designs.

Table I: The Core Parameters of ITER, EAST, FDS-I/-ST AND FDS-EM / -FB / -WT

Parameters	**EAST**	**ITER**	**FEB**	**FDS-ST**	**FDS-I**	**FDS-EM/ -FB / -WT**
Fusion power (MW)	-	500	143	100	150	49
Major radius (m)	1.95	6.2	4	6.2	4	4
Minor radius (m)	0.46	2	1	2	1	1
Aspect ratio	4.2	3.1	4	3.1	4	4
Plasma elongation	1.8	1.85	1.73	1.85	1.78	1.7
Triangularity	0.45	0.33	0.4	0.33	0.4	0.45
Toroidal magnetic field on axis (T)	3.4-4.0	5.3	5.2	5.3	6.1	5.1
Safety factor / q-95	-	3	3	3	3.5	2.03
Plasma current (MA)	1.5	15	5.7	15	6.3	6.1
Average neutron wall load (MW/m2)	-	0.57	0.43	0.57	0.49	0.17
Average surface heat load (MW/m2)	0.1-0.2	0.27	0.1	0.27	0.1	0.1

Fusion gain	-	>10	3	>10	3	0.95
Normalized beta, β_N (%)	-	2.5	3.3	2.5	3	3

In the meanwhile, the conceptual design of fusion–fission hybrid reactors have been carried out at SWIP including Tokamak Commercial Breeder (TCB) and Fusion-Driven Transmutation Reactors (FDTR, CFER-ST) etc.

3. Related Technologies R&D

Within the framework of the hybrid reactor program, China has built and operated four mid-sized tokamaks named HT-7, HL-1/1M, HL-2A and EAST. 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 elongated cross section while the superconducting tokamak EAST and the normal conducting tokamak HL-1/1M have been designed and built by Chinese scientists.

The EAST is the first full superconducting tokamak with a non-circle cross-section of the vacuum vessel and an active cooling of plasma facing components in the world. The experiment is being conducted by Institute of Plasma Physics under the Chinese Academy of Sciences. Construction was completed in March 2006 and on September 28, 2006, "first plasma" was achieved. Recently, more than 60 seconds' repeatable high temperature plasma discharge was obtained with LHCD (Lower Hybrid Current Drive) on EAST in May 2009. Long pulse operations (maximum pulse length of 1000 seconds) will be studied in the EAST tokamak with D-D discharges. EAST will be a test bed for technologies proposed for the ITER project.

In addition to plasma experiments, a series of R&D studies in blanket engineering have been performed in China [16-21]. These include neutronics integral experiments to test tritium breeding, neutron breeding and multiplication, fuel breeding and neutron shielding, and tritium production experiments using a fission reactor at SWINPC (Southwest Institute of Nuclear Physics and Chemistry). Studies of fusion-hybrid related materials, structural materials, tritium breeding materials, tritium permeation barrier materials, plasma facing materials were conducted at ASIPP[22-23], CIAE(Chinese Institute of Atomic Energy), SWIP and IMF(Institute of Modern Physics)/CAS. A series of R&D activities on the structural material China Low Activation Martensitic steel (CLAM) [22] and related blanket technology are being carried out in ASIPP. A series of R&D activities on CLAM and related technology for liquid LiPb blankets of FDS series designs are being carried out in ASIPP under wide collaboration with other institutes and universities in China and overseas institutes, which include composition design, smelting of the steel, impurity control, property tests, techniques for hot isostatic pressing (HIP) joining and coating, experiments on interaction with plasma, activation analysis and work on a database for nuclear materials.

To support the various designs and technologies of the LiPb breeder blankets, LiPb experimental loops have been designed and constructed to follow the different stages of LiPb blankets requirement and for different testing functions in ASIPP [24]. Three thermal convection loops named DRAGON-I/II/III have been built to carry out the compatibility experiment and validate the loop technology, and two multifunctional forced convection loops named DRAGON-IV and DRAGON-V are being built to validate MHD effect and thermal-hydraulics tests. Three sets of He-LiPb dual-coolant auxiliary systems named DRAGON-VI/VII/VIII were designed and will be used for TBM testing of EAST, ITER and China fusion experiment reactor blankets, respectively, in the future.

DFLL (Dual-Functional Lithium Lead)-TBM system [17] and HCSB-TBM (Helium Cooled Solid Breeder) are designated to check and validate the technologies of both the Chinese liquid blanket and solid blanket concepts which are proposed to be tested in ITER. The DFLL-TBM will also be tested in EAST tokamak for validating electro-magnetic and neutronics characteristics before ITER operation.

4. Future Prospect of Fusion-Fission Hybrids

To meet the ever increasing energy requirement due to improvements in the economy and living standard of Chinese people, China will need more than 100 nuclear power plants which will consume large quantities of nuclear fuel and result in the accumulation of a large amount of long-lived nuclear radioactive wastes. Studies of nuclear fuel cycle have shown that it will not be possible to achieve the goal of development of nuclear energy without the contribution of fusion-fission hybrid energy systems based on the U-Pu fuel cycle with the presently known deposits of uranium ore in China. On the other hand, we have to go a long way to realize commercial utilization of pure fusion energy. However, a fusion-fission hybrid system could reduce the requirement on fusion plasma technology and engineering since the hybrid requires less stringent parameters for the fusion core. ASIPP is searching for the most feasible option for hybrid reactor implementation for the next few years. The attractiveness of a fusion-fission hybrid system depends on a number of factors, which include neutronics, materials, and chemical separation considerations, as well as the design of the transmutation system. Feasibility studies have shown that the conventional tokamak physics database and existing technology developed and tested in the ITER R&D program is sufficient to allow for the design and construction of neutron sources for waste transmutation and fuel breeding with modest annual neutron fluence.

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