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Conceptual design of the fusion-driven subcritical system FDS-I

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Abstract

The fusion-driven subcritical system (named FDS-I) was previously proposed as an intermediate step toward the final application of fusion energy. A conceptual design of the FDS-I is presented, which consists of the fusion neutron driver with relatively easy-achieved plasma parameters, and the He-gas/liquid lithium–lead Dual-cooled subcritical Waste Transmutation (DWT) blanket used to transmute long-lived radioactive wastes and to generate energy on the basis of self-sustainable fission and fusion fuel cycle. An overview of the FDS-I is given and the specifications of the design analysis are summarized.

Keywords: Fusion; Blanket; Subcritical; Transmutation; Waste

1. Introduction

The fusion-driven subcritical system has very attractive advantages because of its potential ability to achieve effective transmutation of long-lived radioactive wastes from spent fuel of fission industry, efficient breeding of fissile fuel to supply for fission industry and other near-term applications based on feasible fusion plasma physics and technology [1]. A preliminary concept of the fusion-driven hybrid system (named FDS) had been proposed, as an intermediate step between fission energy and fusion energy applications, on the basis of the previous studies on the fusion–fission hybrid reactors [2,3]. A series of design activities on the FDS-I, which consists of the fusion neutron driver with relatively easy-achieved plasma parameters and the subcritical blanket used to transmute long-lived nuclear wastes and to generate energy on the basis of self-sustaining of tritium needed for fusion reaction in plasma core and plutonium needed for neutron multi-

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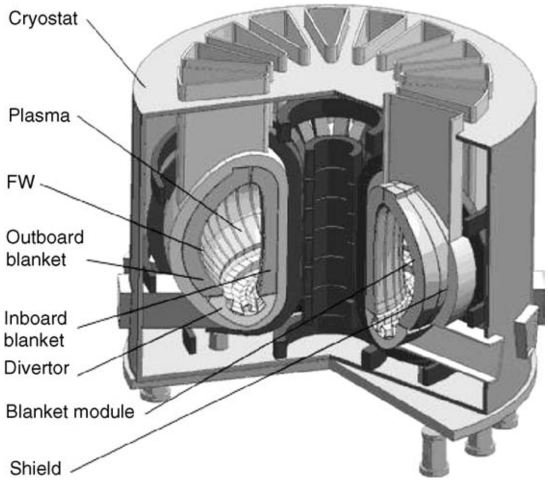

Fig. 1. Overview of FDS-I reference model.

plication in the subcritical blanket, have been being carried out to evaluate and optimize the concept in China [4–8].

An overview of the FDS-I design is presented and FDS-I conceptual study activities are summarized in this contribution. The main reference parameters of the FDS-I design are given, covering plasma physics and engineering of the fusion neutron driver, blanket neutronics, blanket thermal–hydraulics, safety and environmental impact, cost and benefit analysis, etc. An overview of the FDS-I reference model is shown in Fig. 1.

2. Fusion core

The major objective of FDS-I is to demonstrate the feasibility of early application of fusion energy technology. The plasma physics and engineering parameters of FDS-I are selected on the basis of the progress in recent experiments and associated theoretical studies of magnetic confinement fusion plasma, and the progress in studies of blanket concepts optimization to reduce the requirement for neutron source intensity and subsequently for plasma technologies. A set of plasma-related parameters of FDS-I are given in Table 1, as well as those of the International Thermonuclear Experimental Reactor (ITER) [9] for the purpose of comparison. It is understandable that the FDS-I requirement for plasma technology could be met by the development

Table 1
Main core parameters of FDS-I

Parameters	Design	
	FDS-I	ITER
Fusion power (MW)	150	500
Major radius (m)	4	6.2
Minor radius (m)	1	2
Aspect ratio	4	3.1
Plasma elongation	1.78	1.70
Triangularity	0.4	0.33
Plasma current (MA)	6.3	15
Toroidal magnetic field on axis (T)	6.1	5.3
Safety factor (q_{-95})	3.5	3
Auxiliary power (P_{add}) (MW)	50	73
Energy multiplication (Q)	3	≥10
Average neutron wall load (MW m^{-2})	0.5	0.57
Average surface heat load (MW m$^{-2)}$	0.1	0.2

of ITER. More details on design optimization of fusion plasma core are being carried out.

3. Blanket concept and reference module

The general idea of a fusion–fission subcritical system is to have the subcritical blanket which interacts with a copious source of fusion neutrons provided by the fusion core to achieve its multi-functions, such as nuclear waste transmutation, fissile fuel and tritium breeding. The FDS-I blanket design focuses on the technology feasibility and concept attractiveness to meet the requirement for fuel sustainability, safety margin and operation economy. A series of design scenarios, with emphasis on circulating particle or pebble bed fuel forms considering geometry complexity of tokamak and frequency of fuel discharge and reload (including design of an emergency fuel discharge subsystem to improve the safety potential of the system), are being evaluated and optimized considering various blanket module structure and fuel forms. The design and the related analysis of the helium-gas and liquid lithium–lead (LiPb) eutectic Dual-cooled Waste Transmutation (DWT) blanket with carbide heavy nuclide particle fuel in circulating liquid LiPb coolant (named DWT-CPL) are presented in this contribution. Other concepts, such as the DWT blanket with oxide heavy nuclide pebble bed fuel cooled in circulating helium-gas (named DWT-OPG) and with nitride heavy nuclide particle fuel in circulating helium-gas (named DWT-NPG) are also being investigated.

The basic concept of the DWT-CPL blanket had been presented previously in Ref. [10], in which helium gas was adopted to cool the structural walls and long-lived fission products (FP: ^{99}Tc, ^{129}I, ^{135}Cs) transmutation zones (FP-zones) and liquid metal (LM) LiPb eutectic with tiny particle long-lived fuel to self-cool actinide (AC: MA, Pu, U, etc.) zones (AC-zones or LM-zones) including minor actinides (MA: ^{237}Np, ^{241}Am, ^{243}Am, ^{244}Cm) transmutation zones (MA-zones) and uranium-loaded fissile fuel breeding zones (U-zones).

LiPb in AC-zones serves as coolant, tritium breeder and fuel circulating carrier. Pb is also a kind of neutron multiplier. High energy neutrons from D–T fusion reactions and AC fission reactions are moderated in FP-zones with graphite. In the current design, only plutonium (Pu) isotopes from the spent fuel of fission power plants (e.g. PWR) is loaded into the blanket as neutron multiplier instead of part of Pu coming from U-zones, that is, the U-zones are replaced with additional MA-zones, which results in a fertile-free blanket. The reduced activation ferritic–martensitic steel (RAFM, e.g. CLAM) [11] is considered as an alternative structural material because of its good performance in the highly corrosive and radiative environment. The AC appears in the form of the TRISO (TRi-ISOtropic)-like carbide particles coated with SiC suspending in the LiPb slurry. The circulating fuel form has the advantages of good compatibility with complex geometry, easy control of fuel cycle, fast response to emergency fuel removal, etc. The reference module, basic material compositions and radial sizes of DWT-CPL blanket at the tokamak mid-plane of FDS-I are given as in Fig. 2 and Table 2.

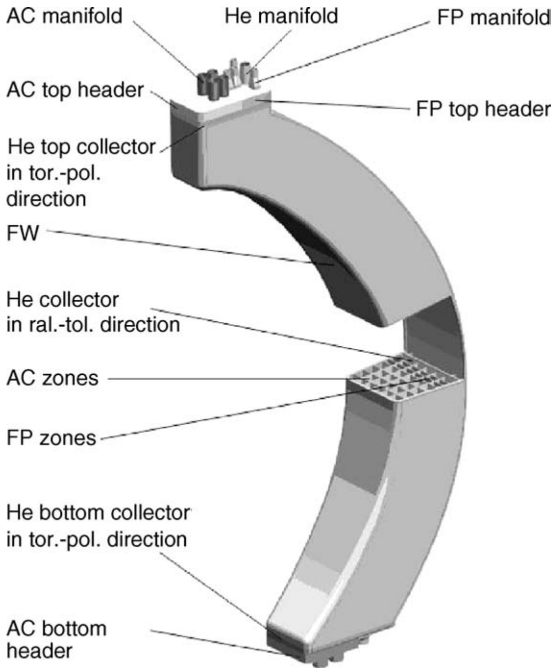

Fig. 2. Reference module of DWT-CPL blanket.

4. Neutronics analysis

The main purpose of neutronics design and analysis is to optimize the composition and spatial arrange-

Table 2
Material compositions and radial sizes of DWT-CPL blanket

Zones	Material component (%)	Thickness (cm)
Inboard blanket		
FW	RAFM steel (45) + He (55)	3
Tritium breeding zone	LiPb (100)	11 × 2
Structural walls	RAFM steel (60) + He (40)	1 × 2
Neutron reflector	Graphite (100)	13
Helium manifold	RAFM steel (40) + He (60)	10
Shield layer	RAFM steel (75) + H_2O (25)	30
Outboard blanket		
FW	RAFM steel (45) + He (55)	3
AC1/AC2/AC3/AC4	MAC (0.6) + PuC (4.3) + LiPb (95.1)	11/11/11/11
Structural walls	RAFM steel (60) + He (40)	1 × 6
FP (CsCl/NaI/Tc)	FP (17.6/1.7/1.5) + graphite (60) + He (22.4/38.3/38.5)	7/7/7
Helium manifold	RAFM steel (45) + He (55)	11
Shield layer	RAFM steel (75) + H_2O (25)	60

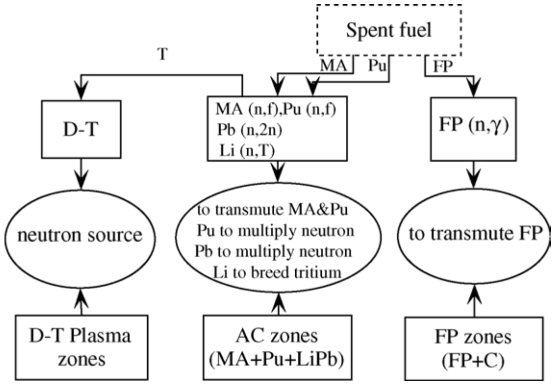

Fig. 3. Neutronics principle of DWT-CPL blanket.

ment of materials in the functional zones and the fuel cycle to achieve highly efficient transmutation of MA with reasonably reduced MA inventory in the blanket, and enough safety margin in normal operation and any transient accidents. The basic neutronics principle and main constraints of DWT-CPL blanket are listed in Fig. 3 and Table 3, where the unit UPWRx is defined as the equivalent amount of identified x-isotopes from the spent fuel at the burnup of 33,000 MWD/MTU from a standard 3000 MW PWR in a full power year.

The main neutronics parameters related to static and dynamic characteristics are given in Table 4 on the basis of neutronics calculations and analysis with the home-developed multi-functional (Sn multigroup neutron transport solution, direct numerical burnup solution and genetic algorithm optimization solution) neutronics code system VisualBUS and the multi-dimensional Monte-Carlo transport code MCNP. Some details on neutronics calculations and analyses can be found in Refs. [5,6].

Table 3
Main constraints and objectives of neutronics design

Items	Constraint and objective
K_{eff}	$\leq$0.95 (safety margin limit)
Pd_{max} (MW m^{-3})	$\leq$100 (cooling capability limit)
TBR	$\geq$1.1 (tritium sustainability limit)
Initial MA/Pu/FP inventory	$\leq$300 $UPWR_{MA/Pu/FP}$ (available waste mass limit and potential hazard limit)
Fuel consumption balance	To keep equivalence of consumed Pu, MA, FP in the unit of UPWR
Transmuted waste per year	To maximize

Table 4
Main neutronics parameters of DWT-CPL blanket

	Reference value
Neutronics parameters	
K_{eff}	0.93
Thermal power (GW)	14.2
Energy multiplication (M)	118
Tritium breeding ratio	3.4
MA transmutation fission ratio WTR_{MA}	0.24
Inventory (kg/UPWR)	
MA	8274/238
Pu	56673/197
FP	8331/200
Consumption per year (kg/UPWR)	
MA	822/24
Pu	6860/24
FP (^{135}Cs/^{129}I/^{99}Tc)	445 (7/9/13)

5. Thermal–hydraulics and thermo-mechanics analyses

The main task of thermal–hydraulics and mechanics analyses is to optimize flow conditions and structural scenario to ensure the high availability of blanket system by evaluating the capability of heat removal of the cooling system and the maximum stress of structure under the conditions of normal operation and accidents. The main thermal–hydraulics and mechanics parameters of the reference module, which are calculated with the commercially available CFD code FLUENT [12] and the thermo-mechanics analysis code ANSYS [13], are listed in Table 5. The velocity profiles of MHD flow in strong field are quite different from those of an ordinary hydraulic flow, which subsequently influences the temperature profile and pressure drop of flow. The MHD effect in the DWT-CPL blanket are being evaluated by empirical equations (see Table 5) and numerical simulation with a home-made program developed on the basis of the commercial code FLUENT. Some details on thermal and mechanics analyses can be found in Refs. [7,14,15].

6. Safety analysis

6.1. Activation characteristics

The FDS-I is designed to pursue a radiologically clean power, i.e. zero net production of long-lived

Table 5
Thermal–hydraulics parameters of DWT-CPL blanket module

Parameters	Value
Helium system	
Inlet/outlet temperature (°C)	250/<450
Velocity in FW ($m\,s^{-1}$)	40
Pressure (MPa)	8
LiPb system	
Inlet/outlet temperature (°C)	250/450
Max. velocity in LM1/LM2/LM3/LM4 zone ($m\,s^{-1}$)	<1.7
Power density in LM1/LM2/LM3/LM4 zone ($MW\,m^{-3}$)	100/90/77/68
MHD pressure drop (MPa)	
With insulating coating	1.2
With flow channel inserts	1.7
Structure wall	
Max. temperature (°C)	469
Max. stress (MPa)	395

radioactive nuclides. The utilization of dedicated fuel (fertile-free) will result in no production of new long-lived MA. The RAFM steel is used as the main structural material to avoid production of long-lived radio-nuclides from the neutron activation reactions. The activation characteristics (dose rate and dominant nuclides) of the FW are calculated and shown in Fig. 4. To support subsequent transient safety analysis on the DWT-CPL blanket, the afterheat in some typical zones in the DWT-CPL blanket is also given in Fig. 5. More details on activation analysis of FDS-I/DWT-CPL blanket can be found in Ref. [16].

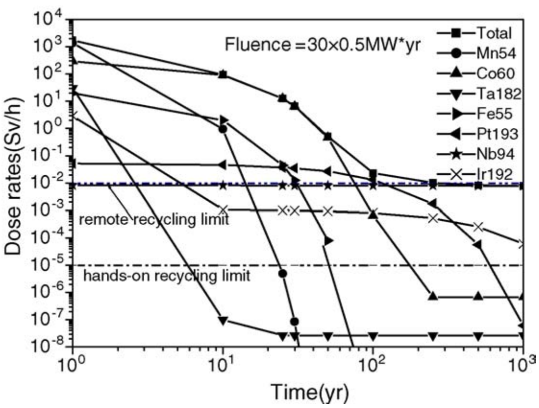

Fig. 4. Dose rate and dominant nuclides of activated FW.

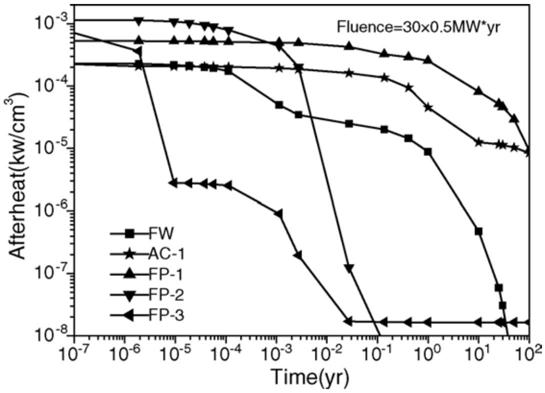

Fig. 5. Afterheat in typical zones in DWT-CPL blanket.

6.2. Transient characteristics

FDS-I is an innovative nuclear system with new features, some of which are related to its transient safety characteristics caused by using the dedicated fuel, although inherent and passive safety measures may be integrated into the defense lines. The temperature reactivity does not cause serious supercritical accidents in a deeply subcritical FDS-I/DWT-CPL reactor. The presence of external neutrons can improve the effective control and safety although the fraction of delayed neutrons is low in the FDS-I/DWT-CPL reactor. The main transient scenarios include ramping of fusion power, plasma disruption, Quench of Super-conducting (QS) in the magnetic field coils, Loss of Flow Accident (LOFA), Loss of Coolant Accident (LOCA), Loss of Heat Sink (LOHS), Transient Over Power (TOP), etc. To assess the safety potential of DWT-CPL blanket, as shown in Table 6, the important neutronics safety parameters and the melting time are calculated in case of some hypothetical severe accidents, such as LOFA/ULOFA (Protected and Unprotected Loss of Flow Accident) and Loss of Power Accident (LOPA), using the above mentioned neutronics, thermal and thermo-mechanics codes. The results show that the afterheat could be efficiently removed when some reasonable safety control sub-systems are integrated. Some details on transient analysis can be seen in Refs. [6,7].

6.3. Probabilistic safety assessment

Probabilistic safety assessment (PSA) is a kind of very useful methodology to assess the safety of a

Table 6
Neutronics safety parameters and the melting time for hypothetical severe accidents

Parameters	Reference value
Doppler coefficients ($p\,\mathrm{cm\,K^{-1}}$)	
BOC	4.6
EOC	−3.6
Void coefficients (p cm/%)	
BOC	301.7
EOC	76.9
Prompt neutron lifetime (s)	1.6E−5
Delayed neutron fraction	200
Melting time of FW (s)	
ULOFA	58
LOFA	15000
LOPA	15000

complex and innovative system like the DWT-CPL blanket, driven by a strong external neutron source, which includes two independent cooling systems, an Emergency fuel discharge system (EFDS) and an emergency plasma shutdown system (EPS). The preliminary PSA of blanket structure melting frequency is carried out, considering the severe accident initiators, such as LOCA, LOFA, QS, TOP, etc., on the basis of the assumption of typical failure data values from fission power plants. The results show that a reasonable design of safety system (FFDS, EPSS, etc.) could reduce the blanket melting frequency to $\sim 1.48 \times 10^{-8}$ per reactor-year, i.e. a few orders of magnitude lower than in a typical PWR (the core melting frequency in the Chinese DAYAWAN power plant is $\sim 4.65 \times 10^{-8}$ per reactor-year), due to the new features of FDS-I/DWT-CPL system. The design with EFDS is very helpful to improve the safety of the system. More details on the PSA of FDS-I can be found in Ref. [8].

7. Summary

The conceptual study activities have been performed to evaluate the feasibility and safety characteristics of the fusion-driven subcritical system designated as FDS-I, consisting of the fusion neutron driver with relatively easy-achieved plasma parameters and the He-gas/liquid lithium–lead Dual-cooled Waste Transmutation blanket with carbide particle fuel in liquid LiPb (named DWT-CPL blanket) used to transmute long-lived nuclear wastes and to generate energy on the basis of self-sustainable fusion fuel cycle. An overview of the system design and the summary of design analysis have been presented. The further detailed design and analyses are needed as a next step.

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References

[1] Y. Wu, A fusion neutron source driven subcritical nuclear energy system: a way for early application of fusion technology, Plasma Sci. Technol. 3 (2001) 1085–1092.
[2] Y. Wu, J.P. Qian, J.N. Yu, The fusion-driven hybrid system and its material selection, J. Nucl. Mater. 307–311 (2002) 1629–1636.
[3] Y. Wu, Progress in fusion-driven hybrid system studies in China, Fusion Eng. Des. 63–64 (2002) 73–80.
[4] Y. Wu, Y. Ke, S. Zheng, W. Wang, D. Chu, Q. Huang, et al., Conceptual design study on the fusion-driven subcritical system (FDS), Chin. J. Nucl. Sci. Eng. 24 (2004) 72–80.
[5] X. Zhu, S. Zheng, J. Li, Analysis on fuel cycle schemes in the fusion-driven subcritical system, (FDS-I), Fusion Eng. Des. 81 (2006) 851–857.
[6] S. Zheng, Y. Wu, Neutronic safety analysis in severe transients of the dual-cooled waste transmutation blanket for the FDS-I, Fusion Eng. Des. 81 (2006) 1425–1429.
[7] Y. Bai, H. Chen, Y. Ke, W. Wang, S. Zheng, Preliminary transient thermal analysis for safety of the dual-cooled waste transmutation blanket for the FDS-I, Fusion Eng. Des., in press.
[8] L. Hu, Y. Wu, Probabilistic safety assessment of the dual-cooled waste transmutation blanket for the FDS-I, Fusion Eng. Des. 81 (2006) 1403–1407.
[9] Technical Basis for the ITER-FEAT Outline Design, G A0 RI 2 00-01-18 R1.0, January 2000. Also see "Summary of the ITER Final Design Report", G A0 FDR 4 01-06-28 R 0.2, July 2001.
[10] Y.C. Wu, X. Zhu, S. Zheng, Y. Ke, Q. Huang, X. Liu, et al., Neutronics analysis of the dual-cooled waste transmutation blanket for the FDS, Fusion Eng. Des. 63–64 (2002) 133–138.
[11] Q. Huang, Q. Huang, J. Yu, R. Wan, J. Li, Y. Wu, The development of low activation martensitic steels for fusion reactor, Chin. J. Nucl. Sci. Eng. 24 (2004) 56–64.
[12] The FLUENT User's Guide, Fluent Inc., January 28, 2003.
[13] ANSYS User's Manual, rev.5.5, Swanson Analysis System, 2000.

[14] W. Wang, Y. Wu, et al., Thermal-hydraulic design and analysis on the dual-cooled waste transmutation blanket for the fusion-driven subcritical system (FDS), Chin. J. Nucl. Sci. Eng. 24 (2004) 93–96.
[15] H. Chen, W. Wang, H. Wang, Y. Bai, Y. Wu, Optimization of first wall structure and shape of helium flow channel of the dual-cooled waste transmutation blanket for the fusion-driven subcritical system (FDS), Chin. J. Nucl. Sci. Eng. 24 (2004) 377–381.
[16] Q. Huang, M. Chen, L. Peng, X. Zhu, Y. Chen, Y. Wu, Activation characteristics of the dual-cooled waste transmutation blanket for the fusion-driven subcritical system (FDS), Chin. J. Nucl. Sci. Eng. 24 (2004) 269–276.