ELSEVIER

Journal of Nuclear Materials 307–311 (2002) 1670–1674

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Neutron radiation effects of the center conductor post in a spherical tokamak reactor

J. Yu [a,*], Y. Wu [b], J. Sha [a], Q. Huang [b], Y. Ke [b]

[a] *China Institute of Atomic Energy, P.O. Box 275-51, Beijing 102413, People's Republic of China*

[b] *Institute of Plasma Physics, P.O. Box 1126, Hefei, Anhui 230031, People's Republic of China*

Abstract

A Li metal center conductor post (Li metal CCP) is proposed for spherical tokamak reactors. The construction and materials of the core assembly for a Li metal CCP are described. 316Ti stainless steel is proposed for the can of the core and cooling tubes. Flowing water inside cooling tubes removes ohmic heat and nuclear heat in the CCP. Thermal hydraulic and neutronic calculations show that the average temperature of the Li conductor in operation is about 86 °C and the resistivity increases by about 20% after one year of operation. After operating one year the Li conductor can be melted by ohmic heating (no cooling water), and the liquid metal passed through a purification system to return the core assembly by an auxiliary liquid metal loop. The purified liquid metal can be cooled down to form the Li conductor again. The advantage of the proposed concept is discussed.

1. Introduction

Spherical, or low aspect ratio, tokamaks (ST) offer attractive potential advantages. These include compact volumetric neutron sources and steady-state operation reactors requiring relatively low external fields due to high performance (high stable β in the first stability boundary) [1–6]. An additional attractive potential application is to transmute long-lived actinides and fission products produced by fission power plants [7,8].

However high β also means a high neutron wall loading, e.g. up to 8 MW/m^2, which can result in severe neutron radiation effects in the first wall (FW), especially in the center conductor post (CCP). A design with an aspect ratio near the lower limit requires an unshielded CCP as part of the toroidal field coil circuit. The exposed CCP will receive severe neutron damage, material transmutation, resistive and nuclear heating, and requires replacement at regular intervals [9–12].

In this study, a lithium metal center conductor post (Li-CCP) is proposed instead of the conventional CCP made of copper alloy. The construction and materials of a Li-CCP are described in Section 2. The average temperature of Li in the CCP is about 86 °C from thermal-hydraulic calculations with the PHOENICS 3.2 code [19]. The proposed Li-CCP has potentially attractive advantages in comparison with the conventional copper alloy CCP. These include less transmutation waste, less electric conductivity change, tolerable neutron irradiation damage, enhancement in tritium breeding ratio and longer service lifetime. The pinch effect only induces a stress in the Li metal in a strong magnetic field and has no significant influence on the engineering.

The key parameters (nuclear heating, resistive heating, displacement per atom (DPA), additional tritium breeding ratio, etc.) of a Li-CCP are calculated and analyzed in Section 3. The damage dose to the lithium metal is calculated to determine the length of the operating period. At the end of the operating period, it must be treated to clear up defects and remove tritium and transmutation wastes. This can be performed by warming up the Li metal to its melting temperature by a heating current and auxiliary liquid metal loop. The

* Corresponding author. Tel.: +86-10 6935 7232; fax: +86-10 6935 7008.

E-mail address: yujn@iris.ciae.ac.cn (J. Yu).

0022-3115/02/$ - see front matter © 2002 Elsevier Science B.V. All rights reserved.
PII: S0022-3115(02)01106-6

tritium produced by the Li-CCP can compensate for the cost of lost electrical power for a machine with a Li-CCP in comparison to a conventional copper alloy CCP.

2. The construction and materials of a Li-CCP

A sketch of a Li-CCP is shown in Fig. 1. It consists of a core 800 mm in external diameter and two bushings 1100 mm in external diameter press fit onto the core ends for a good electrical and thermal contact. The core consists of an upper lid, cone-shaped bottom, dual-sheath can and cooling tubes. The core assembly is filled with Li as a conductor. The cone-shaped lid and bottom are made of Glidcop copper alloy and are joined to the cooling tubes and dual-sheath can by plasma arc welding. The surfaces of the cone-shaped lid and bottom are electroplated with chrome. 316Ti stainless steel is considered as the structure material for the can and cooling tubes. The inner surface of the can and the outer surfaces of the cooling tubes can be coated with Al_2O_3 to prevent tritium permeation.

The purpose of a Li-CCP is to keep the service lifetime of the CCP sufficiently long to avoid regular replacement, as in the case of a conventional CCP made of copper alloy. The conductor cross-section of the bushings is about two times than that of the core assembly and radiation effects on the bushings are not anticipated to influence them. The key point is the core assembly that will receive severe neutron damage, materials transmutation, ohmic and nuclear heating. The Li conductor will operate at a temperature of about 86 °C with cooling water and operates for one period (~1 year). After the operating period, the Li conductor will be melted by ohmic heating in the absence of cooling water, and the liquid metal will pass through a purification system and return to the core assembly by an auxiliary liquid metal loop. The purified liquid metal will be cooled down to form a solid Li conductor again. The solid Li conductor avoids the pinch effects on a liquid metal in a strong magnetic field, and has good compatibility with 316Ti stainless steel in comparison with a liquid metal center post.

The structural materials (316Ti stainless steel) of the dual sheath can and cooling tubes will operate at temperatures less than 100 °C, where there is no radiation swelling and good compatibility with Li and water. Radiation hardening reaches saturation at ~10 dpa and the materials still retain some ductility.

The electrical and thermal conductivity of Na and K are better than that of Li, but the melting points of Na and K are too low relative to the operating temperature. Although a Li conductor enhances the ohmic heating, Li can tolerate the operating temperature and enhances the tritium-breeding ratio. The tritium produced by a Li-CCP may compensate the cost of lost electrical power of a machine using a Li-CCP in comparison with a conventional copper alloy CCP.

The ST and CCP parameters and operating conditions are presented in Table 1. The results of thermal hydraulic calculations with PHOENICS 3.2 code [19] show that the maximum temperature of the Li-CCP is 113 °C and the average temperature is near 86 °C for $a = 0.3$, where a is the ratio of cooling cross-section to the CCP cross-section. The maximum temperature of Li-CCP is 115 °C and the average temperature is near 92 °C for $a = 0.25$. Further calculations for improving the construction of the core assembly will be carried out.

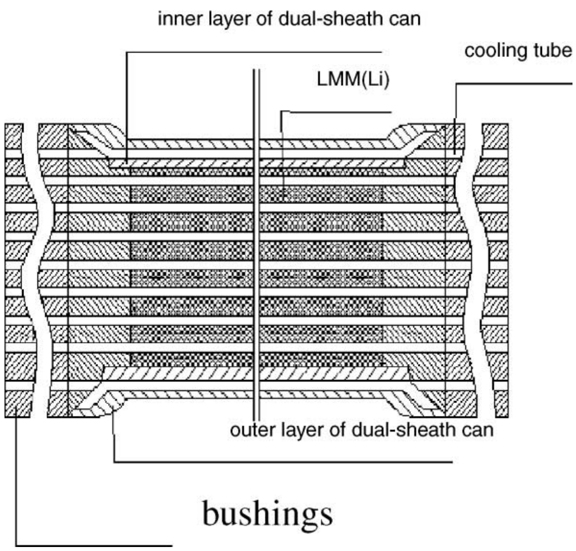

Fig. 1. Construction and materials of core assembly.

Table 1
The main spherical tokamak (ST) and central post (CP) parameters and operation conditions

Minor radius (m)	1.0
Elongation	3.0
Fusion power P_{fusion} (MW)	100
Toroidal field (T)	2.5
TFC total current (MA)	13.8
Minimum CP diameter (m)	0.8
Length of CP part with minimum diameter (m)	2.0
Mid-plane TFC average J_{tf} (MA/m^2)	45.6
Maximum CP diameter (m)	1.1
CP operation mode	Steady-state
Conductor material	Li and glidcop
Coolant	Water
Cooling channel average diameter (m)	0.015
Nuclear heating power (MW)	11
Maximum conductor temperature (°C)	113
Cooling channel pressure drop (MPa)	0.8
Water flow velocity (m/s)	10
Maximum CP ohmic power (MW)	51

3. Radiation damage and tritium breeding

A schematic view of the reference spherical tokamak is depicted in Fig. 2 (geometrical model). The sizes and material compositions are given in Table 2. Based on the above parameters and the geometrical model, the Monte Carlo neutron/photon transport code MCNP/4A [14] was used to calculate the tritium breeding ratio and the DPA in the CCP. The calculated results for the Li-CCP and C-CCP are presented in Table 2, where Li-CCP represents the present CCP concept and C-CCP represents the conventional Cu-based CCP concept. The conditions considered in the calculations were $P_w = 1$ MW/m^2, $I_{post} = 13.8$ MA, where P_w, I_{post} are the neutron wall loading and electric current in the CCP, respectively. More details on the reference reactor can be found in Refs. [8,13]. For the purpose of relative comparison, the conductor service lifetime criteria was assumed to be ~50 dpa averaged over the whole CCP conductor. The DPA values for ITER in Table 2 are taken from Ref. [15].

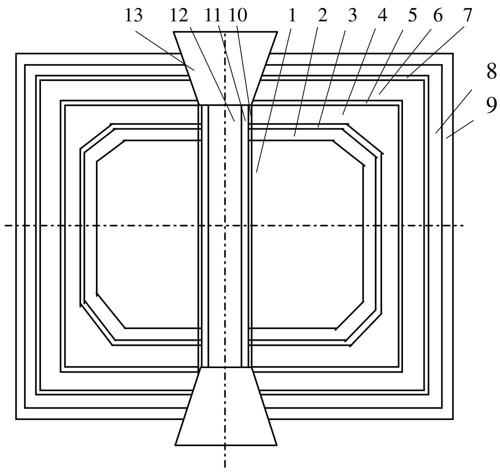

Fig. 2. A geometrical model of the reference designs (numbers correspond to zone numbers in Table 2).

Table 2
Sizes, material compositions for the reference design, and DPA values and parameters for various reactors at $P_w = 1$ MW/m^2

Zone number	Component (material)	Compositions		Radial thickness (cm)	
		Case 1	Case 2		
1	Plasma (void)			200	
2	Scrape-off layer (void)			15	
3, 10	FW (martensitic steel)	9Cr–2W–0.25V–0.07Ta–0.1C	Same as case 1	1	
4	Breeder	77%$Li_{17}Pb_{83}$ + 9%AC[a] + 4% SiC + 10%martenitic steel	Same as case 1	33	
6	Reflector	Graphite	Same as case 1	10	
5, 7	Wall (martensitic steel)	9Cr–2W–0.25V–0.07Ta–0.1C	Same as case 1	1	
8	Shield (martensitic steel)	9Cr–2W–0.25V–0.07Ta–0.1C	Same as case 1	3	
9	Shield structure (martensitic steel)	9Cr–2W–0.25V–0.07Ta–0.1C	Same as case 1	10	
11	Li-CCP dual-sheath	90%316Ti SS + 10%H_2O	Same as case 1	1	
	C-CCP tube	74%Cu + 26%H_2O	Same as case 1		
12	Li-CCP	63.4%Li + 5.6%316Ti SS + 31%H_2O	69.6%Li + 4.7%316Ti SS + 25.8%H_2O	39	
	C-CCP	Cu + H_2O	Same as case 1		
13	Bush	Cu + H_2O	Same as case 1		
Component	Li-CCP	Li-CCP (tube)	C-CCP (whole)	ITER (FW)	ITER (FW)
Material	Li	316Ti SS	Cu	Cu	316SS[a]
DPA/year	~2.4	~10.0	4.0	10.1	9.3
Conductor lifetime (year)			12.5		
Tritium breeding ratio contributed by CCP	0.27 (1.34)[b]		No (1.07)[a]		
Electric resistivity	Controlled		77		
Resistive dissipation power at the end of lifetime (MW)	51		23		
Nuclear heating power (MW)	11		12		

[a] AC, minor actinides + plutonium.
[b] Numbers in parentheses represent the total tritium breeding ratio in the reference design.

Because of electronic losses, only a portion of the full recoil energy T transferred to a PKA, T_{dam}, is available for further displacement. The damage energy T_{dam} normalized to T shows a decrease in T_{dam}/T with increasing recoil energy and decreasing atomic mass of the medium where the PKA is slowing down. Lithium is the lightest metal and a very small portion of a recoils' initial energy is spent on displacement, mainly at the end of the PKA range [16]. Accordingly, the DPA calculation for Lithium in Li-CCP considered a correction factor ($\sim$0.6) for the Lindhard damage efficiency function.

The electrical resistivity of copper and Li at 343 K is assumed to be 2.06×10^{-8} and 11.205×10^{-8} Ωm, respectively [17]. The change in resisitivity for the C-CCP was estimated based on the method described in Refs. [6,9]. The change in resistivity for the Li metal CCP consists of two parts. The first part is the tritium product as a solute atom to induce the increase of resistivity; the second part is the transmutation helium and radiation defects (depleted zone, vacancies, interstitials) to form the microstructure (bubbles, voids, dislocations and dislocation loops) inducing the change of resistivity. Since the lithium temperature range under operation (30–113 °C) is higher than 2/3 melting point (T_m) for lithium metal, the diffusion and accumulation of radiation defects induces bubbles, voids, dislocation loops and network dislocations. Because of the weak scattering of conductive electrons by dislocations, the dislocation terms typically produce less than a 1% of the increase in the resistivity of irradiated copper [18]. The bubbles and voids induce swelling. Experimental studies [18] have confirmed that the swelling contribution to resistivity increase can be described by a simple mixture rule (originally derived by Maxwell), $\rho/\rho_m = [(1+0.5\Delta V)/(1-\Delta V)]$, where ρ_m is the matrix resistivity and V is the volume fraction of cavities. This relationship is valid when the average cavity size is larger than the electron mean free path in the matrix material, which is $\sim$30 nm for pure lithium at room temperature. Assuming a design limit for radiation-induced swelling of 5%, the corresponding resistivity increase is about 8%. The tritium product as a solute atom induces an increase in resistivity, which is similar to a Frenkel pair inducing a change of resistivity. According to a calculated tritium-breeding ratio, the tritium content will be 4500 ppm in lithium metal conductor after operating one year. This induces a resistivity increase of about 0.865×10^{-8} Ωm, which corresponds to a 8.25% resistivity increase. Thus the main contribution to the resistivity increase comes from tritium. If the swelling of Li is about 2% for Li-CCP operating one year, the total resistivity increase is about 12%.

In comparison with C-CCP at 70 °C, the lost electrical power of a Li-CCP at 70 °C is about 36.02 MW. But Li-CCP produces 0.1716 g of tritium/h, which has a value more than 2.5 times the lost electrical power.

4. Summary

A lithium metal CCP concept has been proposed and analyzed for spherical tokamak reactor applications based on the construction and materials design, and thermal hydraulic and neutronic calculations. The calculation results show that the maximum temperature of the Li conductor in operation is 113 °C and the resistivity increases about 12% after operating one year. The Li-conductor irradiated one year can be melted by ohmic heating in the absence of cooling water, and the liquid metal can pass through a purification system to return to the core assembly by an auxiliary liquid metal loop. The purified liquid metal can be cooled down to form a solid Li conductor again. The advantage of the proposed concept has been discussed.

The study has shown that the Li-CCP has potentially attractive advantages. These include less transmutation waste, controlled electric conductivity change, tolerable neutron structured damage, enhancement in tritium breeding ratio and longer service lifetime time compared to the conventional copper alloy CCP. The solid Li metal CCP avoids the pinch effects of a liquid metal CCP in a strong magnetic field.

Further engineering design and the analysis are needed to make this concept available.

References

[1] Y.K.M. Peng, D.J. Strickler, Nucl. Fusion 26 (1980) 769.
[2] Y.-K.M. Peng, J.B. Hicks, Paper presented at the Symposium on Fusion Technology, London, 1990.
[3] 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, China, 30 October–November, 1995.
[4] D.C. Robinson et al., CN-60/F-I-3(1), Paper presented at the 15th IAEA Fusion Energy Conference, Seville, Spain, 26 September–1 October, 1994.
[5] D.C. Robinson, R. Buttery, I. Cook, et al., The way forward for the spherical tokamak, Paper presented at the 12th Topical Meeting on the Technology of Fusion Energy, Reno, NV, 16–20 June, 1996.
[6] R.D. Stambaugh, V.S. Chen, R.L. Miller, M. Schafer, Fusion Technol. 33 (1998) 1.
[7] Y.C. Wu, L.J. Qiu, Y.X. Chen, et al., Waste transmutation and energy generation in spherical tokamak hybrid reactor, Paper presented at 20th Symposium on Fusion Technology, Marseille, France, 7–11 September, 1998.
[8] L.J. Qiu, Y.C. Wu, B.J. Xiao, et al., A low aspect ratio tokamak fusion neutron driven transmutation system, Paper presented at the 17th IAEA Fusion Energy Conference, Yokahama, Japan, 19–24 October, 1998.

[9] Y. Wu, B. Xiao, Q. Huang, L. Qiu, Fusion Technol. 35 (1999) 1.

[10] L.L. Snead, D. Steiner, Center conductor design for the compact spherical torus reactor, Proceedings of the IEEE 13th Symposium on Fusion Engineering, Knoxville, TN, vol. 2, 2–6 October, 1989, p. 890.

[11] E.T. Cheng et al., Fus. Eng. Des. 38 (1998) 219.

[12] I.N. Sviatoslavavsky, Y.-K.M. Peng, E.T. Cheng, et al., Fusion Technol. 30 (1996) 1649.

[13] Y. Chen, Y. Wu, Conceptual study on high performance blanket in a spherical tokamak fusion-driven tranmuster, Paper presented at the 5th International Symposium on Fusion Nuclear Technology, Rome, Italy, 19–24 September, 1999.

[14] J.F. Briesmeister, MCNP4A – A general Monte Carlo N-particle transport code, Los Alamos National Laboratory, LA-12626-M, Los Alamos, NM, 1993.

[15] Detail of the ITER outline design report, ITER-TAC-4-07, for ITER TAC Meeting No. 4, 10–12 January 1994, presented by the ITER director.

[16] W. Schilling, H. Ullmaier, Physics of Radiation Damage in Metals, Materials Science and Technology, vol. 10B, VCH, 1994, p. 187.

[17] D.R. Lide, Handbook of Chemistry and Physics, 79th Edn., 1998–1999.

[18] S.J. Zinkle, S.A. Fabritsiev, Atom. Plasma-Mater. Interact. Data Fusion 5 (1994) 163 (supplement to the J. Nucl. Fusion).