Analysis on Tritium Management in FLiBe Blanket for LHD-Type Helical Reactor FFHR2*)

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In FFHR2 (LHD-type helical reactor) design, FLiBe has been selected as a self-cooling tritium breeder for low reactivity with oxygen and water and lower conductivity. Considering the fugacity of the tritium, particular care and adequate mitigation measures should be applied for the effectively extracting tritium from breeder and controlling the tritium release to the environment. In this paper, a tritium analysis model of the FLiBe blanket system was developed and the preliminary analysis on tritium permeation and extraction for FLiBe blanket system were done. The results of the analysis showed that it was reasonable to select W alloy as heat exchanger (HX) material, the proportion of FLiBe flow in tritium recover system (TRS) was 0.2, the efficiency of TRS was 0.85 and tritium permeation reduction factor (TPRF) was 20 in blanket etc.. In addition, further R&D efforts were required for FFHR2 tritium system to guarantee the tritium self-sufficient and safety, for example reasonable quality of tritium permeation barriers on blanket, requirement for the TRS and fabrication technology of the heat exchanger etc..

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1. Inroduction

Force-free helical reactor (FFHR) is a demo-relevant helical-type D-T fusion reactor based on the great amount of R&D results obtained in the LHD project. FLiBe has attractive merits on safety aspects: low tritium solubility, low reactivity with air and water, low pressure operation, and low MHD resistance which is compatible with high magnetic field designs. Thus FLiBe has been selected as a self-cooling tritium breeder in FFHR2 designs [1].

Tritium is one of the nuclear fuels and the significant radioactive sources for fusion reactors. Thus the tritium control in a breeding blanket is a key issue in terms of both tritium self-sufficiency and safety of the fusion plant. Considering the fugacity of the tritium and its low solubility in FLiBe, particular care and adequate mitigation measures are to be applied in the FLiBe blanket system in order to keep the tritium release rate to the environment below the allowable level i.e.10 Ci/day [2].

In this paper, preliminary sensitive analysis on tritium management in FLiBe blanket of FFHR2 has been done. The factors which affected tritium extraction and permeation were calculated and evaluated, such as the different heat exchanger, proportion of FLiBe flow in tritium recover system (TRS), efficiency of TRS, and tritium permeation reduction factor (TPRF) in blanket etc. The analysis results were given, and a conclusion has been made.

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2. Analysis Method and Model for Tritium Mass Balance

The tritium flow model of the entire FFHR2 blanket system was developed, which included the FLiBe blanket and major components of the auxiliary system. A schematic chart of this model was shown in Fig. 1.

Based on the tritium flow mode, a simplified tritium analysis model for FLiBe blanket system was developed, and shown in Fig. 2. Utilizing the mass balance theory, an equation can be written as:

$$\frac{\partial M_{\mathrm{T/FLiBe}}}{\partial t} = J_1 - J_2 - J_3 - J_4 - J_{\mathrm{D}} \quad (1)$$

where $M_{\mathrm{T/FLiBe}}$ is the tritium inventory in FLiBe, J_1 is tritium production rate, J_2 is tritium extraction from breeder, J_3 is tritium permeation from breeder, J_4 is tritium permeation into coolant, J_{D} is tritium radioactive decay in breeder.

In the liquid FLiBe, the tritium chemical form is T_2 [1]. At fast liquid FLiBe flow velocity, the helium rise in liquid breeder ($Li + n \rightarrow T + He$), then the convection produced by temperature gradients will develop an approximate uniform tritium concentration in the blanket. In this analysis,we use average tritium concentration in breeder

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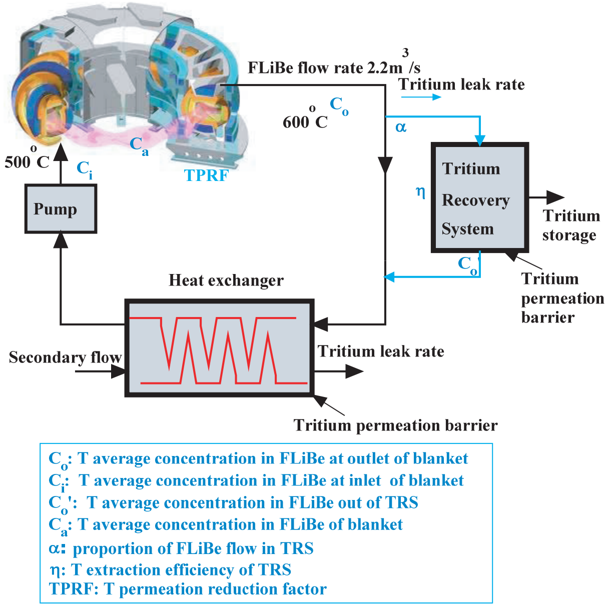

Fig. 1 Tritium flow model of FFHR-2 system.

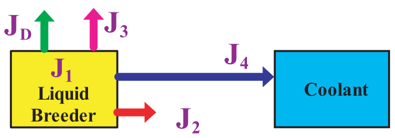

Fig. 2 Tritium analysis model for FLiBe blanket.

(C_a), neglect the tritium transport in the liquid breeder and consider only the diffusion in the steel walls to get conservative permeation result [3]. The average concentration (C_a) and tritium partial pressure (P) were calculated by the following formula:

$$C_a = \frac{C_i + C_o}{2} = \left(1 - \frac{1}{2}\alpha\eta\right) C_o \tag{2}$$

$$P = \frac{C}{K_H} \tag{3}$$

where K_H is tritium gas solubility constant for the molten salt (FLiBe), η is efficiency of TRS, α is proportion of FLiBe flow into TRS.

In blanket, the tritium in FLiBe will diffuse into the structural material, and then permeate through blanket to other devices. To simulate this process, the diffusion limited permeation model was used. In the model, the tritium permeation flow rate (J) through a wall is proportional to the difference of the square roots of tritium partial pressures [4]:

$$J = \frac{1}{\mathrm{TPRF}} \frac{A}{d} D_s K_s \sqrt{P_a} \tag{4}$$

where K_s is tritium solubility in structure material, D is tritium diffusivity in structure material, and A is permeation area, d is the permeation distance, P_a is tritium average partial pressure. By means of the formula above, permeation from FLiBe system (J_3), and the permeation into secondary coolant in HX (J_4) were all considered in detail.

In the TRS, the tritium will be extracted from FLiBe and transport to the reactor core as a fuel supply. The extraction flux (J_2) is calculated:

$$J_2 = \alpha\eta_{\mathrm{FLiBe}} G_{\mathrm{FLiBe}} C_o = \alpha\eta_{\mathrm{FLiBe}} G_{\mathrm{FLiBe}} K_{\mathrm{Ho}} P_o \tag{5}$$

where G_{FLiBe} is liquid breeder flow rate of FLiBe, P_o is the tritium partial pressure at outlet.

For short half-life of tritium, the radioactive decay can't be neglected. In this case, the tritium radioactive decay flux (J_D) represents the tritium inventory of decay in FFHR2 blanket, and can be calculated by following formula.

$$J_D = \lambda V_{\mathrm{FLiBe}} C_a = \lambda V_{\mathrm{FLiBe}} \left(1 - \frac{1}{2}\alpha\eta_{\mathrm{FLiBe}}\right) K_{\mathrm{Ho}} P_o \tag{6}$$

where λ (decay factor) is 5.64 %/yr, V_{FLiBe} is volume of breeder.

3. Conditions for Analysis

In FFHR2 operation, the fusion power is designed to be 1 GW and the flow rate of FLiBe to be 4.4×10^6 g/s (the density FLiBe is 2×10^6 g/m^3). And the volume of FLiBe is estimated to be ~430 m^3. In steady state, the maximum tritium production rate is estimated to be 190 g/day [5,6] to get conservative result of tritium management, especially the tritium permeation analysis Then tritium transported to TRS and extracted from FLiBe, the maximum efficiency of TRS is selected as 0.98. The tritium solubility in FLiBe (K_H) as T_2 is 5.3×10^{-13} wtfr/Pa [6].

Refer to the designs of blanket and the auxiliary system of FFHR2, structure and material parameters of these components are showed in Table 1. And the tritium related parameters are presented in Table 2:

Table 1 Structure and material for FFHR2 blanket.

Component	A (m^2)	d (m)	T (°C)	Material
Blanket [7]	489	0.010	550	JLF-1
HX [8]	700	0.001	550	Ta/Nb/W/Sic
Pipe from blanket to TRS	10	0.005	600	SS316
Pipe from TRS to HX	15	0.005	600	SS316
Pipe from HX to blanket	15	0.005	500	SS316

Table 2 Tritium permeability for materials.

F82H (550°C) [11]	5.06×10^{-11} g/m.s.Pa$^{0.5}$
through W (600 °C) [11]	1.09×10^{-13} g/m.s.Pa$^{0.5}$
through SiC (600°C) [12]	5.24×10^{-19} g/m.s.Pa$^{0.5}$
through Nb (600 °C) [8]	1.18×10^{-9} g/m.s.Pa$^{0.5}$
through Ta (600 °C) [13]	3.23×10^{-7} g/m.s.Pa$^{0.5}$
through sus316 (600°C) [4]	9.7×10^{-11} g/m.s.Pa$^{0.5}$

- For the FLiBe corrosion and neutron irradiation, it is considered to fabricate tritium permeation barrier on the exterior of FLiBe blanket, and the maximum TPRF is 50 referenced other liquid blanket design [9].
- All the auxiliary piping have an aluminize coating on the exterior, and the TPRF would reach 1000 for a 50 µm layer [10].
- The SiC composite and W have low tritium permeability, thus it don't need fabricate tritium permeation barrier on the substrate material surface.

4. Analysis and Results

4.1 Sensitive analysis

4.1.1 Effect of different heat exchanger

In this case, α was 1, η was 0.98 and TPRF in blanket was 50, the tritium extraction and permeation were calculated by changing the heat exchanger material without coating, and the results were showed in Figs. 3, 4. Selected Nb alloy and Ta alloy as HX material, most of tritium would permeate into secondary loop for their high tritium permeability. While SiC composite and W alloy have low tritium permeability, thus less tritium would permeate into secondary loop but more would be extracted. In addition, considering the difficulty of SiC fabrication based on current technology, W alloy was more reasonable selection for HX structure material [14].

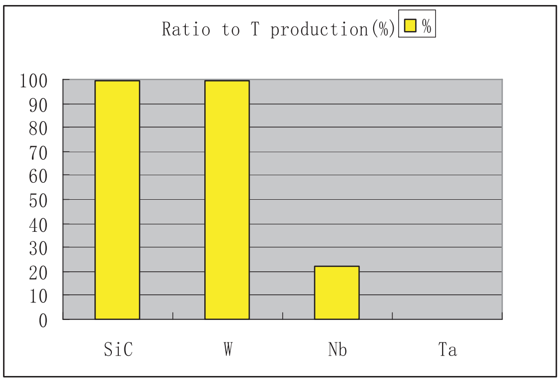

Fig. 3 T recovery vs. HX.

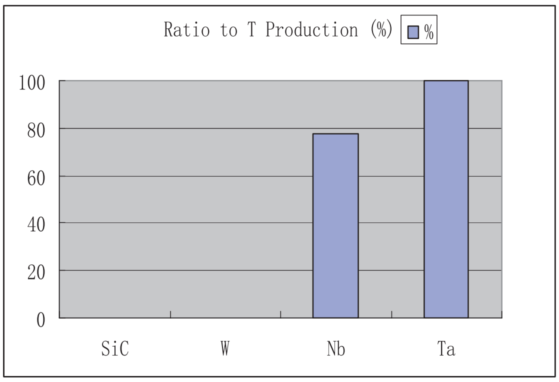

Fig. 4 T leak into secondary flow vs. HX.

4.1.2 Effect of FLiBe flow in TRS (α)

In this analysis, using W alloy as HX material, η was 0.98 and TPRF in blanket was 50, the tritium extraction and permeation were calculated by changing α. The results were showed in Figs. 5, 6. When α reach to 0.2, tritium extraction and permeation would be changed slowly with an increasing α, and the change limit in 1 % when α increase from 0.2 to 1. More FLiBe flow into the TRS, the requirement of TRS would be increased and more heat in FLiBe would be lost in TRS. The analysis showed that it was reasonable to choose proportion of FLiBe into TRS as 0.2 for FLiBe blanket design.

4.1.3 Effect of efficiency of TRS (η)

In the analysis, the HX material was W alloy α was 0.2 and TPRF in blanket was 50 the tritium extraction and average pressure in FLiBe were calculated by changing η. As showed in Figs. 7, 8, when η increased from 0.01 to 0.98, tritium extraction from FLiBe would be increased little (from 94.5 % to 98.3 %). But the tritium average pressure in FLiBe would be reduced largely (from ~44000 Pa to ~4300 Pa). High tritium pressure in FLiBe means high tritium inventory in blanket, which would increase the potential dangers for fusion reactor operation. For safety reason, it needed get high η to reduce the tritium inventory in

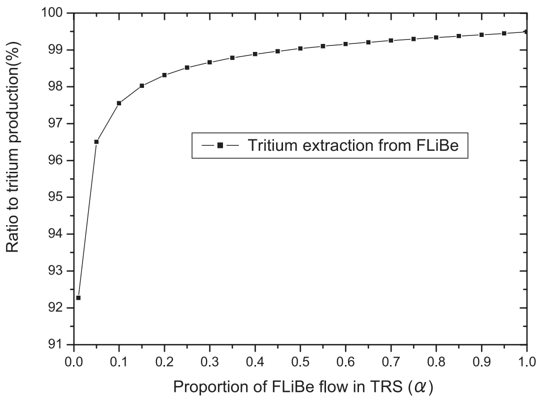

Fig. 5 T recovery vs. α.

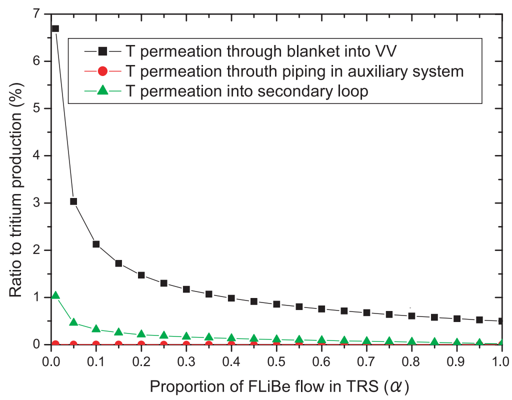

Fig. 6 T permeation vs. α.

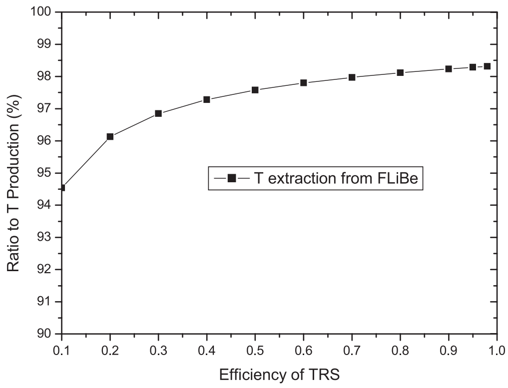

Fig. 7 T recovery vs. η.

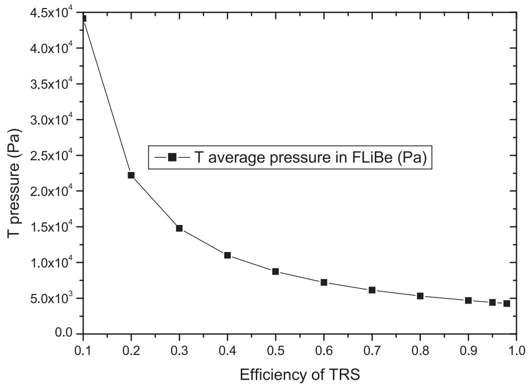

Fig. 8 T pressure vs. η.

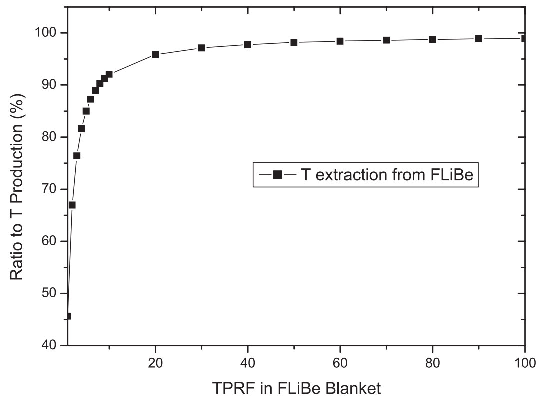

Fig. 9 T recovery vs. TPRF.

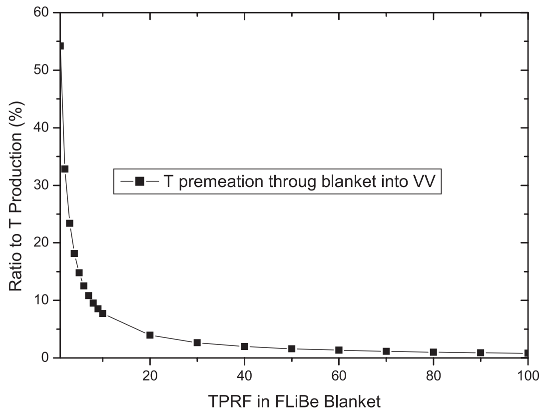

Fig. 10 T permeation through blanket vs. TPRF.

FLiBe, which would increase the requirement of technology and cost for TRS. So it was needed to design reasonable efficiency for the TRS. The tritium average pressure in FLiBe would below 5000 Pa when η reaching 0.85. Maybe η as 0.85 was an acceptable design.

4.1.4 Effect of TPRF in FLiBe blanket

In the analysis, the heat exchanger material was W alloy, α was 0.2 and η was 0.85, the tritium extraction and permeation were calculated by changing the TPRF on FLiBe blanket. The results were shown in the Figs. 9, 10.

When the TPRF reached ~20 or became larger on blanket, more than ~95 % of bred tritium would be recovered from FLiBe, and the tritium average pressure in FLiBe and permeation through blanket would change slowly. Thus it was reasonable to choose TPRF for 20 on FLiBe blanket in FFHR2 tritium system design. It didn't need to get very high quality tritium permeation barrier for FLiBe blanket. However, the permeation barrier compatible with good thermal conductivity was essential.

4.2 Analysis results

Basing on the sensitive analysis, the tritium extraction, permeation and tritium pressure in FLiBe were calculated, where HX material was W alloy, α was 0.2, η was 0.85 and TPRF was 20 in blanket respectively. The results are showed in the Table 3:

Table 3 Tritium analysis results of FLiBe blanket for FFHR2.

	1.7251E+06 Ci/day
T permeation into VV	7.0683E+04 Ci/day
T leak from blanket to TRS	1.1578E+01 Ci/day
T leak from TRS to HX	1.5822E+01 Ci/day
T leak from HX to blanket	1.5822E+01 Ci/day
T leak through secondary flow	4.1386E+03 Ci/day
T decay in FLiBe	3.2205E+00 Ci/day

- The fusion power of FFHR2 is 1 GW, which means 1.4495E+06 Ci-T/day will be burned up in plasma. Tritium recovered from FLiBe in TRS is 1.7251E+06 Ci/day (9.5841E+01 %), which is enough for FFHR2 burn up.
- The tritium permeation through blanket into VV is 7.0683E+04 Ci/day, which must be transported to isotope separation system (ISS) by vacuum pump and stored for fueling. According to ITER design [15], the impurity stream from VV is disposed to reduce

the tritium content by a factor of $\sim 10^7$ before releasing into the atmosphere, thus most of tritium permeation into VV will be reused and the tritium release into environment from VV can be neglected.

- The total tritium permeation rate into the auxiliary system building is 4.3223E+01 Ci/day. To keep the tritium release into environment below the allowable level i.e. 10 Ci/day, an effective Vent Detritiation System (VDS) is needed for FFHR2 to process all effluent gas from reactor confinement building for final detritiation before release into the environment.
- Tritium permeation into secondary loop can't be neglected (4.1386E+03 Ci/day), thus an effective coolant purification system (CPS) should be designed for FFHR2.

5. Conclusions

In this paper, a tritium analysis model of the FLiBe blanket system was developed and the factors which affected tritium extraction and permeation were calculated and evaluated The results showed that it was reasonable to select W alloy as heat exchanger material, α was 0.2, η was 0.85 and TPRF in blanket was 20 etc.

Based on the assumed operation condition, tritium recovery from FLiBe in TRS was enough for FFHR2 burn up. To control the tritium leak rate into auxiliary system building less than 10 Ci/day, an effective VDS was needed for FFHR2 to process all effluent gas from reactor confinement building. And an effective CPS should be designed for secondary loop.

In addition, further R&D efforts were required for FFHR2 to guarantee the tritium self-sufficiency and safety, for example fabrication technology of the heat exchanger, requirement for the TRS and reasonable quality of tritium permeation barriers on blanket, etc.

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