ELSEVIER Journal of Nuclear Materials 258–263 (1998) 2079–2082

journal of nuclear materials

Materials design and related R&D issues for the force-free helical reactor (FFHR)

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Abstract

Materials issues related to the Force-Free Helical Reactor (FFHR) design are presented. In FFHR, which uses the Flibe liquid breeder from the main reason of safety, if there is no need to replace in-vessel materials in the lifetime of 30 years, the reactor can be operated with not only the high safety margin but also a high availability of the plant, resulting in reducing not only the cost of electricity (COE) but also the total amount of radiative wastes. Nuclear properties of induced radioactivity, solid transmutation products, and decay heat at the 14 MeV neutron fluence of 45 $\mathrm{MWa/m^2}$ as well as materials compatibility with Flibe are investigated for JLF-1, V-alloy, SiC and high Z materials. In conclusion, control of metal impurities, transmutation of W and V, acceptable decay heat, and reaction kinetics with Flibe are pointed out as R&D issues.

1. Introduction

The Force-Free Helical Reactor, FFHR [1–3], is a demo relevant helical-type D-T fusion reactor based on the Large Helical Device, LHD, which is the first all-superconducting (SC) coils device and is now under construction in NIFS [4,5]. Owing to inherently currentless plasma, helical-type reactors have attractive advantages such as steady operation and no dangerous current disruption. The force-free-like coil configuration, where the magnetic hoop force between helical coils is reduced, gives three advantages: (1) simplification of coil support structures which gives wide open areas for replacing in-vessel components, (2) widening of the coil-to-plasma clearance needed for the blanket and shielding space, and (3) use of high magnetic fields instead of high plasma beta, $\langle\beta\rangle$, with requiring less-severe enhancement for energy confinement.

Since the major radius R of FFHR is as large as 20 m with the fusion output of 3 GW, the neutron wall loading is reduced to as low as 1.5 $\mathrm{MW/m^2}$ in average, which leads to the neutron irradiation damage of about 450 dpa in the reactor lifetime of 30 years. For the blanket design, the Flibe molten-salt of composition LiF–$\mathrm{BeF_2}$ operated above 450°C has been selected as a self-cooling tritium breeder from the main reason of safety [6]: low tritium inventory, low reactivity with air and water, low pressure operation, and low MHD resistance which is compatible with our high magnetic field design.

Here, in general, the liquid breeder does not require periodic replacement of blankets like solid breeders. Then, if there is no need to replace in-vessel materials in the lifetime of FFHR, the reactor can be operated with not only the high safety margin but also a high availability of the plant, resulting in reducing not only the cost of electricity (COE) but also the total amount of radioactive wastes. Therefore, besides the high heat and particle flux issues, the materials integrity at high

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PII: S0022-3115(98)00242-6

neutron fluence and compatibility with Flibe are the key issues to realize replacement free FFHR.

This paper mainly focuses studies on nuclear properties of blanket structural materials, by discussing the issues of induced radioactivity, solid transmutation products, and decay heat at the level of 45 MWa/m^2. Material issues of compatibility with Flibe are also discussed. The objectives of the present study are to collect knowledge for predicting materials performance in the FFHR condition and to identify supporting R&D issues.

2. FFHR blanket design

The reactor parameters have been described in detail in a previous paper [3]. Under the force-free-like coils configuration, we selected almost optimum parameters for self-ignition with the magnetic field B_0 of 12 T, the plasma aspect ratio R/a_p of 10, and the coil-to-plasma clearance Δ of 1 m for the blanket and shielding.

Fig. 1 shows the current design of the FFHR blanket, which has been almost optimized to have the local tritium breeding ratio (TBR) of 1.2 with saving the total amount of Be and shielding the fast neutron flux more than 5 orders in magnitude at the SC coils [7].

For the first wall materials, by allowing of maintenance in every 10 years, materials reliable up to 120 dpa are reasonably used. However, the goal remains for 30 year lifetime without maintenance. After considering engineering databases and radioactivity, a ferritic steel JLF-1 (Fe9Cr2W) has been selected as the first candidate. Vanadium alloy or ODS steel are second options [8]. If SiC materials is technologically available in future, it gives high thermal efficiency with He gas turbine systems, because the design window of Flibe itself is open and better at higher temperature regions.

The liquid breeder inlet temperature 450°C was determined from the melting temperature and viscosity of Flibe [9]. The outlet temperature has been determined from creep strength of JLF-1. Under conditions of creep strain less than 0.5% at 100 MPa for the lifetime of 120 dpa, JLF-1 is hopefully used at temperatures around 550°C, because the creep coefficient of this material is relatively low among similar low activation steels [10], and because the Flibe coolant can be operated at a very low pressure, possibly below 1 MPa [11].

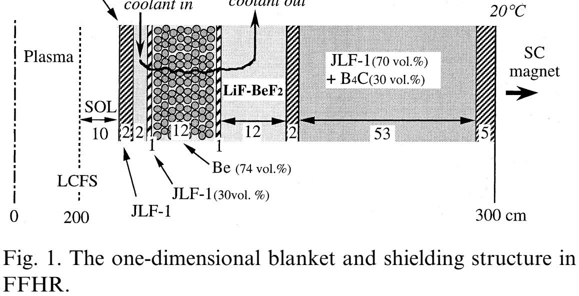

Fig. 1. The one-dimensional blanket and shielding structure in FFHR.

3. Nuclear issues of blanket structural materials at 45 MWa/m^2

3.1. Induced radioactivity

After operation to 45 MWa/m^2 in FFHR and 100 years cooling, the surface dose rate of JLF-1 and of the V-alloy(V5Cr5Ti) is less than 1 μSv/h. This level satisfies the shallow land disposal limits such as Class C limits of US 10CFR61 or the allowable hands-on dose rate of 10 μSv/h [12].

On the other hand, in case of pure SiC, the dose rate decreases down to the level of 10 μSv/h within 10 years, and this level does not decrease any more for more than 100,000 years as shown in Fig. 2. However, from the point of view of the shallow land disposal limits, pure SiC is also one of materials available up to 45 MWa/m^2.

As for bulk impurities, the concentrations of Mo and Nb must be lower than 10 ppm as shown in Fig. 3. These concentrations are rather severe values, and may require advances in materials purification methods beyond present-day technologies.

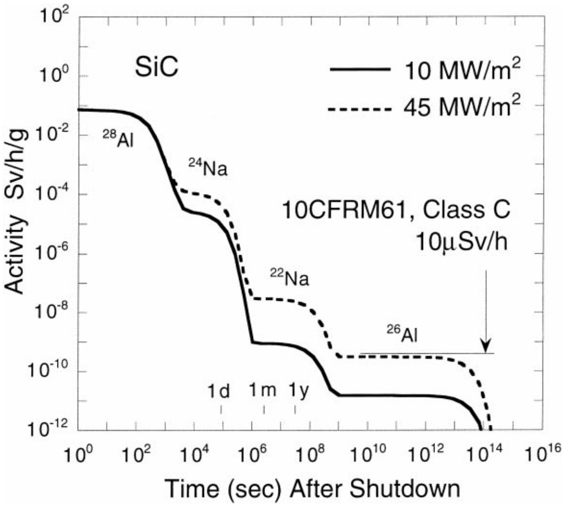

Fig. 2. Decay behaviors of the surface dose rate of pure SiC located at the first wall of FFHR.

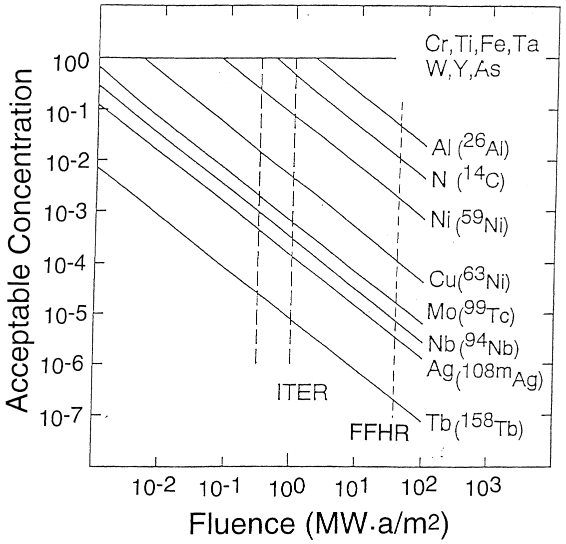

Fig. 3. Acceptable concentrations of first wall materials under the Class C limit of 10CFRM61.

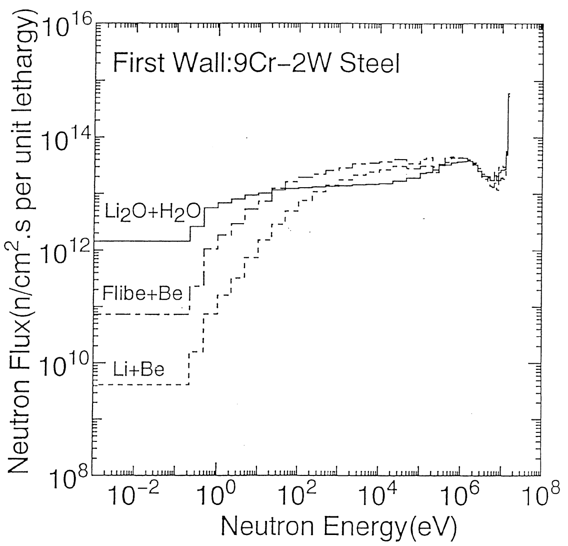

Fig. 5. Neutron energy spectra at the first wall of FFHR for various breeder/shielding compositions.

3.2. Solid transmutation products

In case of JLF-1, transmutation of W is remarkable as shown in Fig. 4, where W mainly changes to Re, and Re changes to Os [13–15]. Finally, after the operation of 45 MWa/m^2, the atomic composition changes from 100% W to almost 10% W, 20% Re and 70% Os. Investigation of materials properties of JLF-1 after large transmutation of W element are needed.

In case of V-alloy, the main concern is the compositional increase in Cr due to the transmutation of V, resulting in the sharp increase of the DBTT with the increase of Cr over the critical 6 wt% [16]. It has already be known that, when the neutron flux below 100 eV is high as in case of solid breeder with stainless steel/water shielding, the Cr concentration increases about 2 wt% per 10 MWa/m^2, but it is only 0.25% in case of a Li–V blanket due to the fairly low flux below 100eV [15]. Here, in case of Flibe blanket, since the neutron energy spectrum is fairly hard in the range below 100eV as shown in Fig. 5, the increase of Cr is estimated to be about 2 wt% in 45 MWa/m^2. Therefore V–4Cr–4Ti alloy has a sufficient margin regarding to the DBTT shift under the 14 MeV neutron fluence of 45 MWa/m^2.

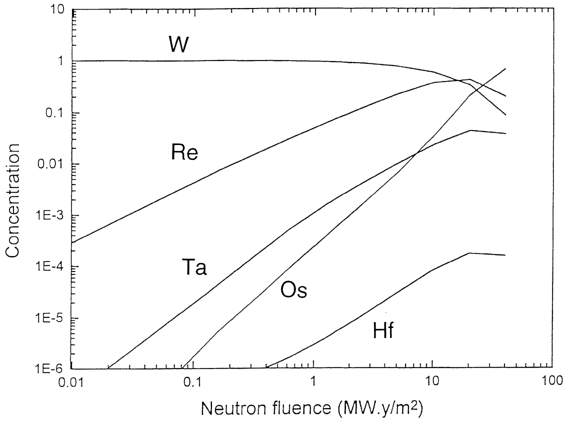

Fig. 4. Concentration changes of metallic elements in W as a function of neutron fluence.

3.3. Decay heat

From the point of view of machine safety and maintenance, decay heat Q_d (W/g) of blanket materials after terminating the reactor operation must be always taken into account. Under adiabatic condition, the temporal increasing rate of bulk temperature T(°C) is expressed as $dT/dt = Q_d/C_v$, where C_v (J/g/°C) is the specific heat. The acceptable decay heat depends on actual blanket structures. However, Fig. 6 clearly means that the Q_d/C_v with C_v of 0.15 for Ta becomes almost 15°C/s for 100 days and this level of decay heat is not acceptable. As for W, Mo and Nb, for instance, the Q_d/C_v is less than 0.5°C/s after 1 week cooling, and this level of decay heat is possibly in the controllable range.

4. Materials issues on compatibility with flibe

The compatibility between Flibe and most structural materials has been one of major issues [8,11]. Since Flibe itself is very stable (free energy of formation DG^{f}_{1000K} of

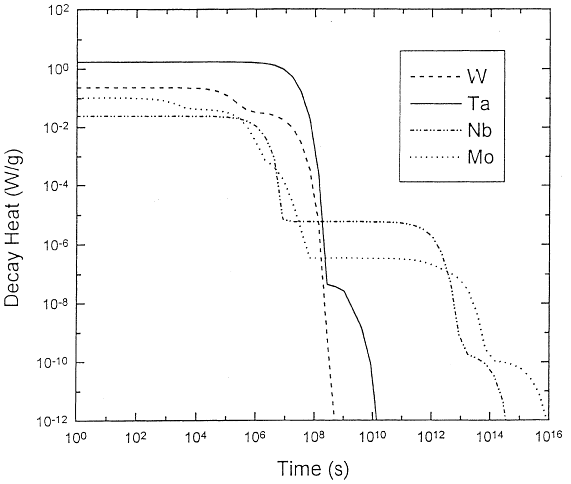

Fig. 6. Changes of decay heat in typical metals after 10 MWa/m^2 irradiation.

BeF_2 and LiF are −106.9 and −125.2 kcal/g-atom F, respectively), the corrosion is caused by the impurities in FLiBe. In the tritium breeder, there is some possibility that TF can be formed (DG^{f}_{1000K} of TF is −66.2 kcal/g-atom F), which is very corrosive to most structural materials. The FFHR design has two scenarios to overcome this problem by using Be and MoF_6. The neutron multiplier Be is used as the metal scavenger ($Be + 2TF \rightarrow BeF_2 + T_2$) to reduce the amount of severely corrosive TF molecules. On the other hand, though TF is very corrosive to Fe based and V based alloys, resistance of W and Mo against the TF corrosion is very high. So MoF_6 (DG^{f}_{1000K} is −50.2 kcal/g-atom F) can be often used to form protection layers of Mo deposited on the surface of the coolant tube with the reaction ($MoF_6 + 3T_2 \rightarrow 6TF + Mo$). Here the produced TF is again reduced by the reaction with Be. Data bases on chemical kinetics in these reactions are strongly desired.

5. Conclusion

Nuclear properties of induced radioactivity, solid transmutation and decay heat under the 14 MeV neutron fluence of 45 MWa/m^2 have been investigated on candidate materials for the Flibe blanket in FFHR as well as materials compatibility with Flibe. Conclusions are as follows.

1. The surface dose rate of JLF-1, V-alloy and pure SiC satisfy the shallow land disposal limits or the hands-on dose rate of 10 μSv/h after 100 years cooling.
2. The concentrations of Mo and Nb impurities must be lower than 10 ppm.
3. Investigation of materials properties of JLF-1 after transmutation of W to 20% Re and 70% Os are desired.
4. For the DBTT shift the V4Cr4Ti alloy has the margin of 2 wt% increase of Cr due to the Flibe blanket.
5. Temperature rise less than 0.5°C/s due to decay heat after 1 week cooling of such as W, Mo and Nb is possibly acceptable for machine maintenance except for Ta which gives 15°C/s for 100 days.
6. The neutron multiple Be is expected to reduce the corrosive TF in Flibe, where the research on reaction kinetics are strongly desired.

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