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Impact of Tritium Removal and He-3 Recycling on Structure Damage Parameters in a D-D Fusion System

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Abstract

Removing tritium produced by D-D fusion and recycling part of it after it decays to He-3 significantly reduces the fraction of fusion energy carried by neutrons in a D-D system. For a catalyzed D-D system (no tritium removal), the peak dpa rate in candidate structural materials is 25-35% lower than that in an equivalent D-T system with the same fusion power wall loading. The gas production and transmutation rates are ~60% lower. As tritium is removed gas production and transmutations decrease by more than two orders of magnitude and the dpa rate decreases by a factor of 2.3-2.8. An additional reduction of a factor of 1.6-1.7 in damage parameters is achieved by recycling the removed tritium as He-3. This results in significant lifetime enhancement of structural materials. Information from tests in fission reactor spectra would be directly relevant in determining the lifetime of the structural material in this He-3-recycled system.

1. Introduction

The two branches of the D-D fusion reaction produce He-3 and tritium. The only neutrons produced are medium-energy DD neutrons (2.45 MeV). If the produced He-3 is not removed, it will react with deuterium producing charged particles (p and He-4) with no additional neutrons. On the other hand, if the produced tritium is not removed, it will react with deuterium producing high-energy DT neutrons (14.1 MeV). In a catalyzed D-D system where all the produced He-3 and tritium are allowed to burn, equal numbers of DD and DT neutrons are generated. In this case, the neutrons carry 38.3% of the fusion energy compared to 80% in a D-T system. Several conceptual designs were presented in the past for catalyzed D-D commercial fusion plants [1,2]. In a catalyzed D-D system there is still a significant amount of DT neutrons produced that could lead to considerable structural radiation damage resulting in limited lifetime of the chamber components.

We propose developing large D-D magnetic fusion power plants in which the amount of tritium allowed to burn is systematically lowered, resulting in a reduced fraction of fusion energy carried by DT neutrons [3]. The D-He-3 reaction produces a large amount of fusion energy that is carried only by charged particles. If part of the tritium removed is allowed to decay and is recycled as He-3, further reduction in the fraction of fusion energy carried by neutrons can be achieved. In this work, we assess the impact of lowering the amount of tritium burned in a D-D system, with recycling of the He-3 produced from tritium decay, on the peak damage parameters in candidate first wall/blanket/shield structural materials. The results are compared to those in a D-T system with the same fusion power wall loading.

2. Energy spectrum of produced neutrons

The energy spectrum of neutrons produced in a D-D system includes two components at 2.45 MeV and 14.1 MeV. The relative number of neutrons at these two energies depends on the fraction of tritium removed (f_{TR}) and the fraction of removed tritium that is recycled as He-3 (f_{Rec}). Figure 1 shows the fraction of fusion energy carried by neutrons. It is clear that significant reduction in the fraction of energy carried by neutrons is achieved as one moves from a fully catalyzed D-D system (f_{TR}= 0) to a system with a large amount of tritium being removed. Recycling the He-3 obtained from the decay of the removed tritium also results in reducing the fraction of fusion energy carried by neutrons. In a fully catalyzed system, 38.3% of the fusion energy is carried by neutrons (32.6% by DT neutrons and 5.7% by DD neutrons). This reduces to only 5.6% carried by DD neutrons if all tritium is removed and recycled as He-3.

For the purpose of comparing the results to those in a D-T system, we normalized to the same fusion power that corresponds to a peak neutron wall loading of 4 MW/m^2 in a D-T system. This implies a total fusion power wall loading of 5 MW/m^2 from both neutrons and charged particles. The neutron wall loading in the equivalent catalyzed D-D system (f_{TR}= 0) is 1.92 MW/m^2 and decreases as the fraction of tritium removed increases. Notice that we assume that the D-D system will have the same size as the D-T system. This is a conservative assumption since D-D systems are expected to be relatively larger than D-T systems leading to an additional reduction in neutron wall loading. Figure 2 illustrates the impact of tritium removal on the energy spectrum of generated neutrons. While in a fully catalyzed D-D system, half of the neutrons are at 14.1 MeV, all the neutrons are at 2.45 MeV in a system with complete tritium removal.

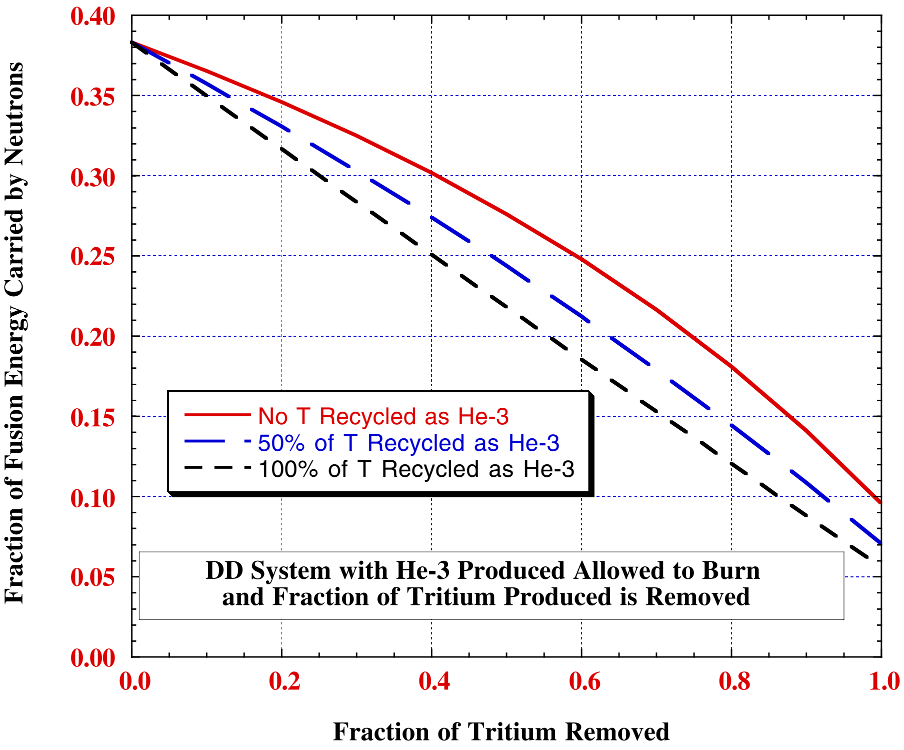

Figure 1. Impact on fraction of fusion energy carried by neutrons.

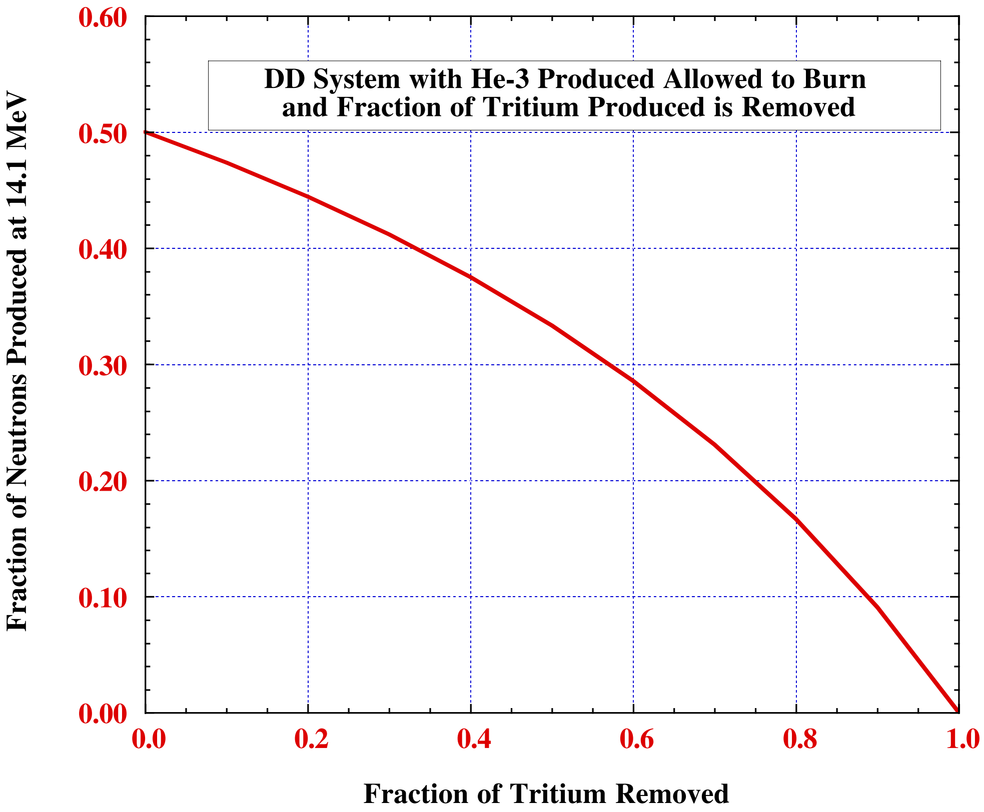

Figure 2. Fraction of neutron energy spectrum at 14.1 MeV.

3. Calculation procedure

The structural material candidates considered are vanadium alloy V4Cr4Ti, ferritic steel alloy 9Cr-2WVTa, and SiC/SiC composite. Although we are interested mainly in the peak damage parameters occuring in the first wall (FW), the blanket was included in the model to account for neutron backscattering. Three candidate breeding blankets were considered. These are $Pb_{83}Li_{17}$ cooled SiC/SiC, Li cooled vanadium alloy, and water cooled ferritic steel (FS) with Li_2O ceramic breeder. Natural lithium is used except in the case of the $Pb_{83}Li_{17}$ eutectic where Li is enriched to 90% Li-6.

In general, a tritium breeding blanket is not needed in a D-D system. However, the bred tritium from the blanket can be extracted and allowed to decay to He-3 that can be recycled in the D-D plasma or used in other D-He-3 systems. To isolate the effect of reduced neutron power and softer neutron spectrum, we compared the damage parameters using the same blanket concept in D-T and D-D systems. Replacing the tritium breeding blanket by a more effective shield reduces the radial build resulting in a smaller and lower cost system. That is in addition to eliminating the need for a tritium handling and extraction system and reducing the blanket tritium inventory. To assess the combined effect of the fuel cycle and elimination of breeding blanket we determined the peak radiation damage parameters for a water cooled FS shield in the D-D system.

The damage parameters calculated are the atomic displacement rate, the helium production rate, the hydrogen production rate and the total transmutation or burnup rate. The ONEDANT module of the DANTSYS 3.0 discrete ordinates particle transport code system [4] was used with the Fusion Evaluated Nuclear Data Library, FENDL-2 [5]. The cross section library includes all partial reaction cross sections required to deterime gas production and transmutations. In addition, it includes the damage energy cross sections needed to determine atomic displacements. We determined the dpa cross sections using displacement energies for the constituent elements of the vanadium and steel alloys provided by Greenwood and Smither [6]. For the SiC/SiC composite, the average displacement energies for the Si and C sublattices were taken to be 40 and 20 eV, respectively [7].

4. Results for Li/V blanket concept

In the D-T system, the peak dpa, He production, H production, and burnup rates are 45.5 dpa/FPY, 177.6 He appm/FPY, 984 H appm/FPY, and 0.116% burnup/FPY, respectively. Transmutations of V yield Ti and Sc and the alloying elements Cr and Ti transmute into V, Ti, Sc, and Ca. Figure 3 shows the FW damage parameter rates as a function of the fraction of tritium removal in the D-D system with all the tritium removed recycled as He-3. For a catalyzed D-D system (no tritium removal), the peak dpa rate is 30% lower than that in the equivalent D-T system. The gas production and transmutation rates are 60% lower.

As the fraction of tritium removed is increased, the damage parameters decrease. The reduction is more pronounced for gas production and transmutations which decrease by about two orders of magnitude with full tritium removal. The dpa rate decreases by a factor of 2.5. The He/dpa ratio drops below one appm/dpa when more than 75% of the tritium is removed. Although He embrittlement depends on numerous factors, it typically becomes a concern for He levels above ~100 appm and operating temperatures above half the melting temperature [8]. Similarly, He production has a diminishing (although non-negligible) impact on cavity swelling as the He/dpa ratio falls below 1 appm/dpa. Hence, the structural material lifetime will likely be determined by atomic displacement issues which can be assessed using tests in fission reactor spectra. Although the dpa rate cannot be reduced by more than a factor of 3.6 compared to the D-T system, the accompanying significant

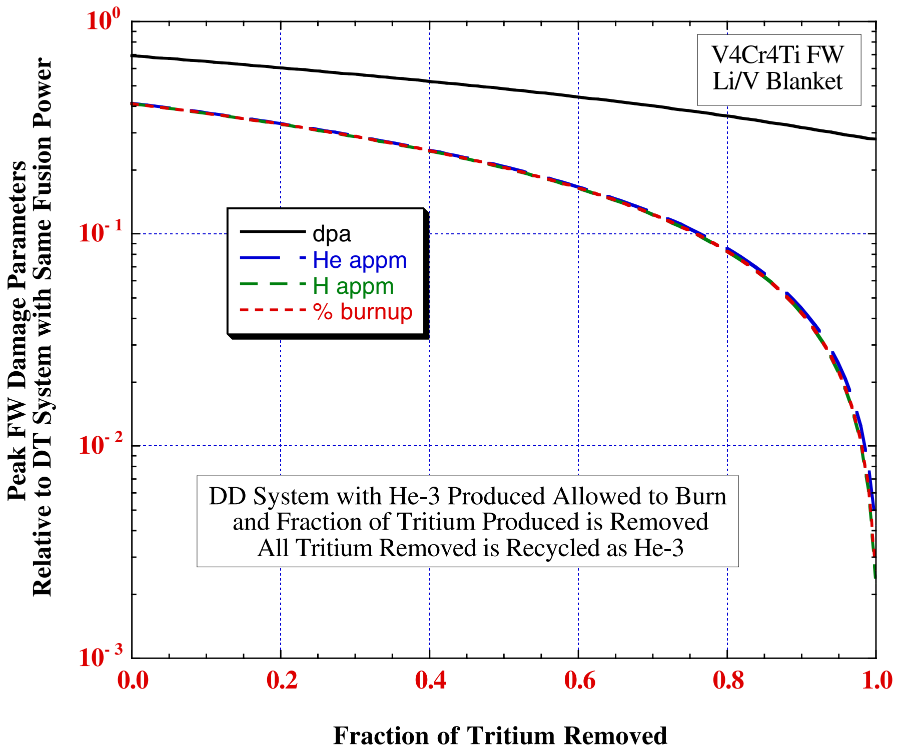

Figure 3. Peak damage parameters in vanadium as a function of tritium removal fraction in D-D system.

reduction in gas production can lead to a larger lifetime enhancement compared to that indicated by the dpa rate reduction.

Figure 4 demonstrates the change in dpa and He production rates as one moves from a D-T system to equivalent D-D systems with different fractions of tritium removal. The range of dpa and He production for V alloys in fission test reactors and different zones in fission power reactors is indicated in the figure. Rates up to 40 dpa/FPY and 1 He appm/FPY can be obtained in fission test reactors. It is clear that removing the produced tritium from the D-D system results in dpa and He production rates that approach values in fission test reactors.

The effect of the fraction of tritium removed that is recycled as He-3 is illustrated in Figure 5. The effect is more pronounced when a large fraction of tritium is removed. With all the tritium being removed, the damage parameters are a factor of ~1.7 lower for the case when all the removed tritium is recycled as He-3 compared to the case without He-3 recycling. While the results indicate that the enhancement of the structure lifetime is more sensitive to the fraction of tritium removed than to the He-3 recycling fraction, the up to a factor of 1.7 enhancement in lifetime with He-3 recycling is still a significant improvement.

5. Results for LiPb/SiC blanket

The peak damage parameters at the FW were determined for both the carbon and silicon sublattices of the SiC/SiC composite structure. In the D-T system, the peak dpa, He production, H production, and burnup rates in the C sublattice are 50.4 dpa/FPY, 3442.9 He appm/FPY, 0.7 H appm/FPY, and 0.121% burnup/FPY, respectively. The corresponding values in the Si sublattice are 40.4 dpa/FPY,

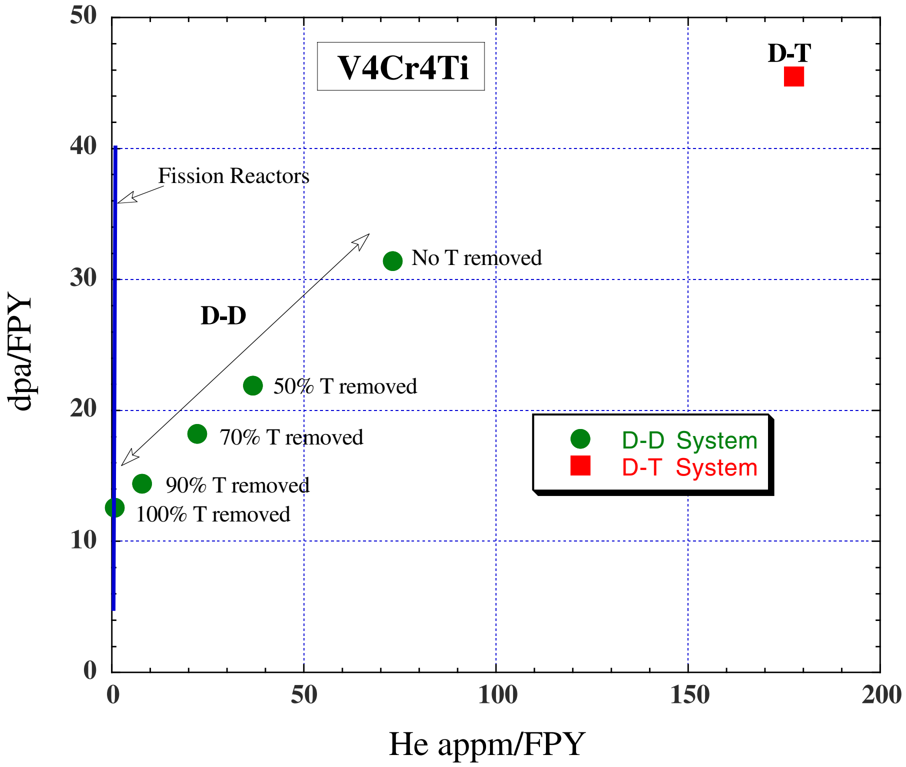

Figure 4. dpa and He production rates in vanadium for equivalent D-T and D-D systems.

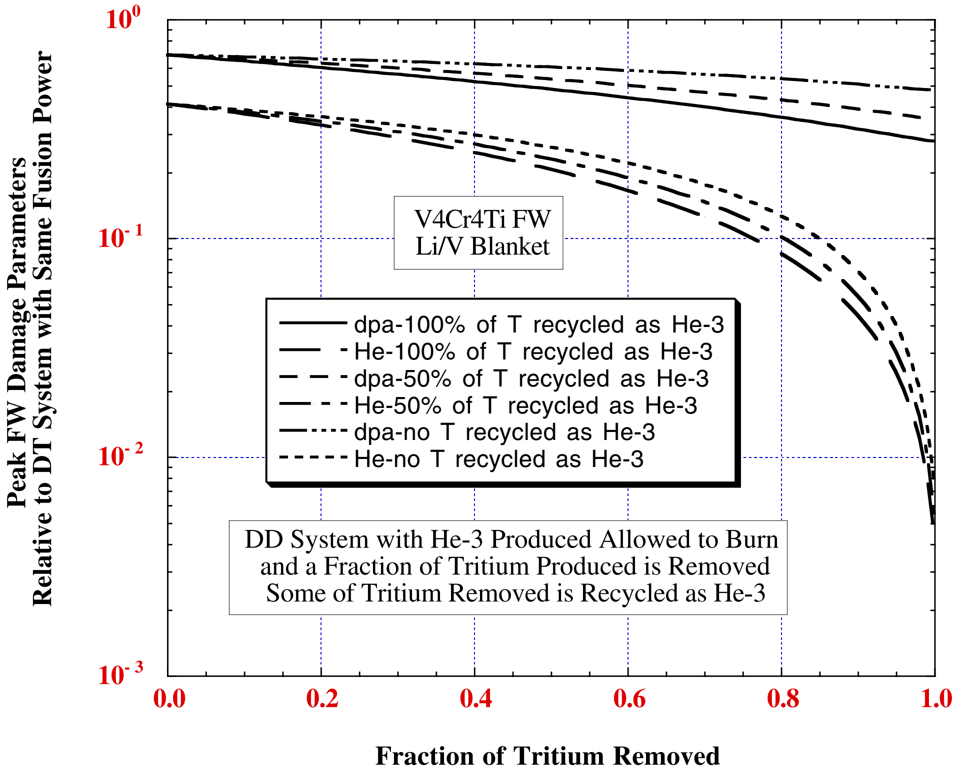

Figure 5. Peak dpa and He production in vanadium as a function of tritium removal fraction and He-3 recycling in D-D system.

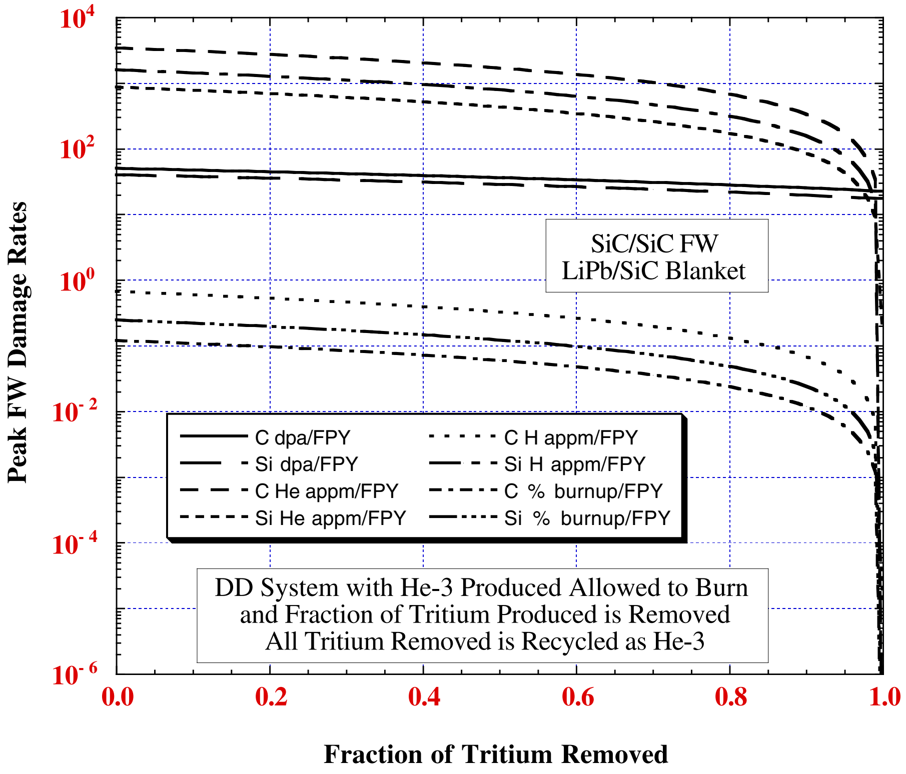

Figure 6. Peak damage rates in SiC/SiC composite as a function of tritium removal fraction in D-D system.

873.8 He appm/FPY, 1593.5 H appm/FPY, and 0.247% burnup/FPY, respectively. The large helium production in C is dominated by the (n,n'3α) reaction. Despite the factor of 4 higher helium production in C compared to Si, the Si burnup rate is twice the C burnup. The large H production in Si contributes to the large Si burnup. The transmutation products include Al, Mg, Be, B, and Li.

The results for the D-D system are shown in Fig. 6. For a catalyzed D-D system, the peak dpa rates are about 25% lower than those in the equivalent D-T system. The gas production rates and burnup rates are 60% lower. These relative improvements are almost identical to those obtained for the V4Cr4Ti alloy. Figure 7 shows the average dpa and He production rates in SiC. Rates up to 40 dpa/FPY and 200 He appm/FPY are obtained in fission test reactors. Again, it is clear that removing the produced tritium from the D-D system results in dpa and He production rates that approach values in fission reactors.

The dpa rate decreases by a factor of ~2.3 for both sublattices with full tritium removal. Even more significantly, the gas production and burnup rates decrease by an order of magnitude with 90% tritium removal and drop sharply as one approaches full tritium removal. This implies that if the lifetime of the SiC/SiC composite is influenced primarily by gas production or burnup, a significant enhancement of lifetime can be achieved by removing most of the tritium and recycling it as He-3. In this case, information from tests in fission reactor spectra will be useful in determining the lifetime of the structural material.

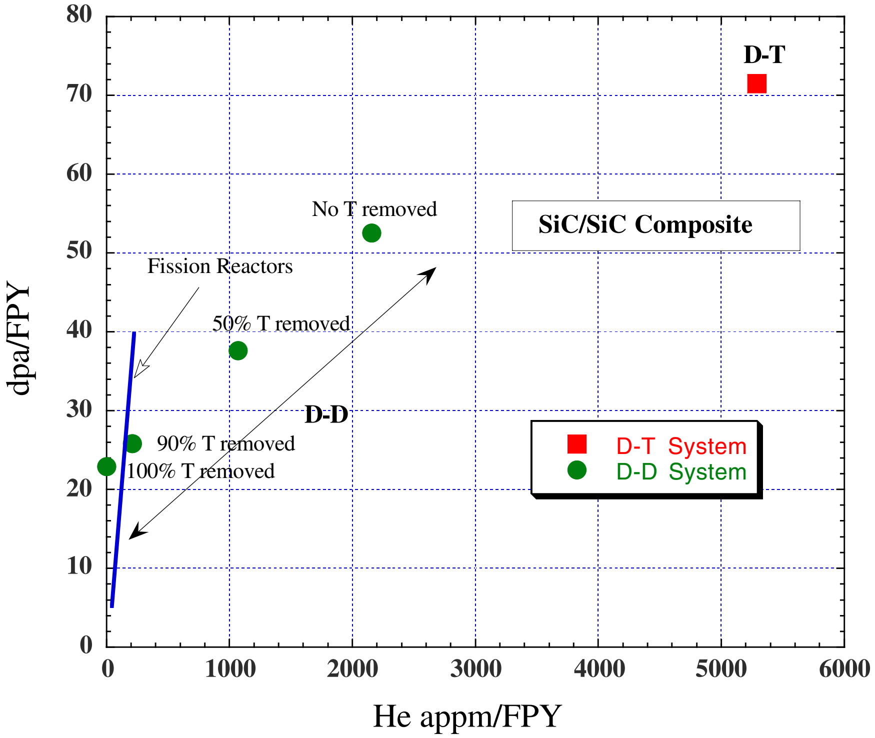

Figure 7. dpa and He production rates in SiC for equivalent D-T and D-D systems**.**

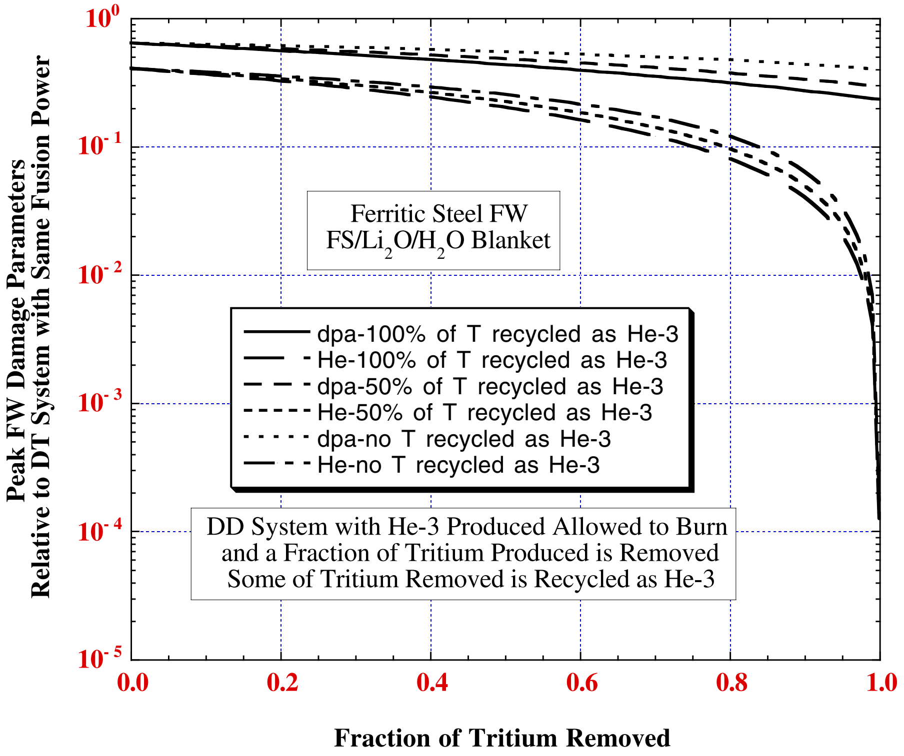

Figure 8. Peak dpa and He production in ferritic as a function of tritium removal fraction and He-3 recycling in D-D system.

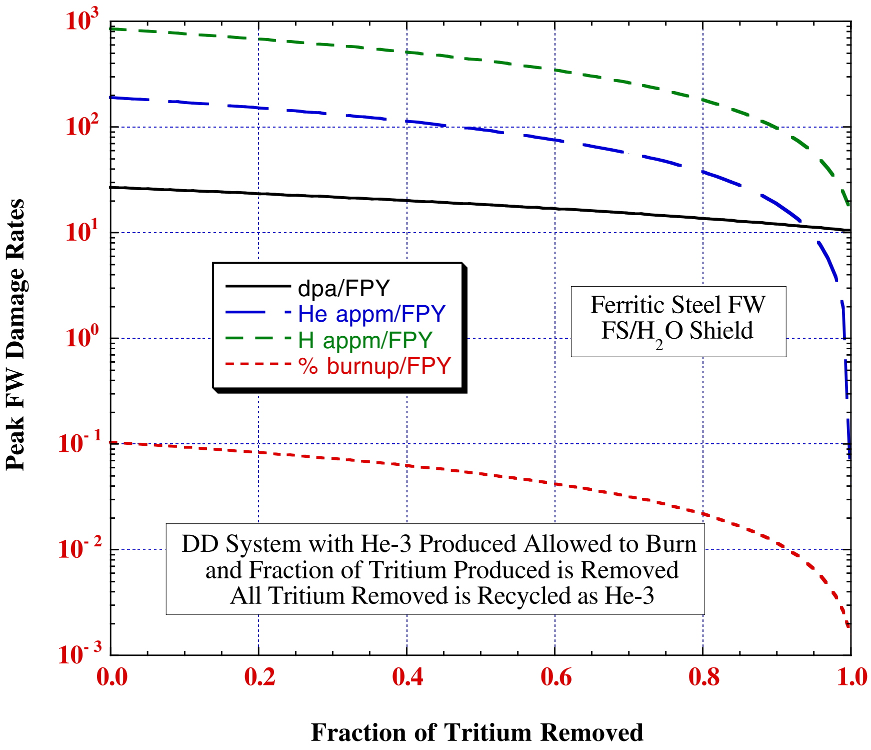

Figure 9. Peak damage rates in ferritic steel as a function of tritium removal fraction in D-D system.

6. Results for FS/Li_2O/H_2O blanket concept

In the D-T system, the peak FW dpa, He production, H production, and burnup rates for this blanket are 38.6 dpa/FPY, 481 He appm/FPY, 2104 H appm/FPY, and 0.259% burnup/FPY, respectively. Transmutations of Fe yield Mn and Cr and the major alloying elements Cr and W transmute into V, Ti, Ta, and Hf. For a catalyzed D-D system, the peak dpa rate in the ferritic steel FW is 35% lower than in the equivalent D-T system. The gas production and transmutation rates are ~60% lower. These relative effects are similar to those obtained for the Li/V and LiPb/SiC blanket concepts. Figure 8 shows the damage parameters in a D-D system as a function of the fraction of tritium removed and fraction recycled as He-3.

As the fraction of tritium removed is increased, the damage parameters decrease. The largest reduction is in the He production rate that decreases by nearly four orders of magnitude when all the tritium is removed. On the other hand, the dpa rate decreases by only a factor of 2.8. Again, as obtained for the Li/V and LiPb/SiC blanket concepts, the gas production and transmutation rates are an order of magnitude lower than those in an equivalent D-T system when more than 75% of the tritium is removed from the D-D system. In this case, the lifetime will be determined primarily by atomic displacement damage issues and information from tests in fission reactor spectra will be useful in determining the lifetime.

7. Results for FS/H_2O shield

In a D-D system significant savings in size and cost is achieved by eliminating the need for a tritium breeding blanket. We performed calculations for a FS/H_2O shield in a D-D system with different tritium removal and He-3 recycling fractions. Figure 9 gives the peak FW dpa, He production, H

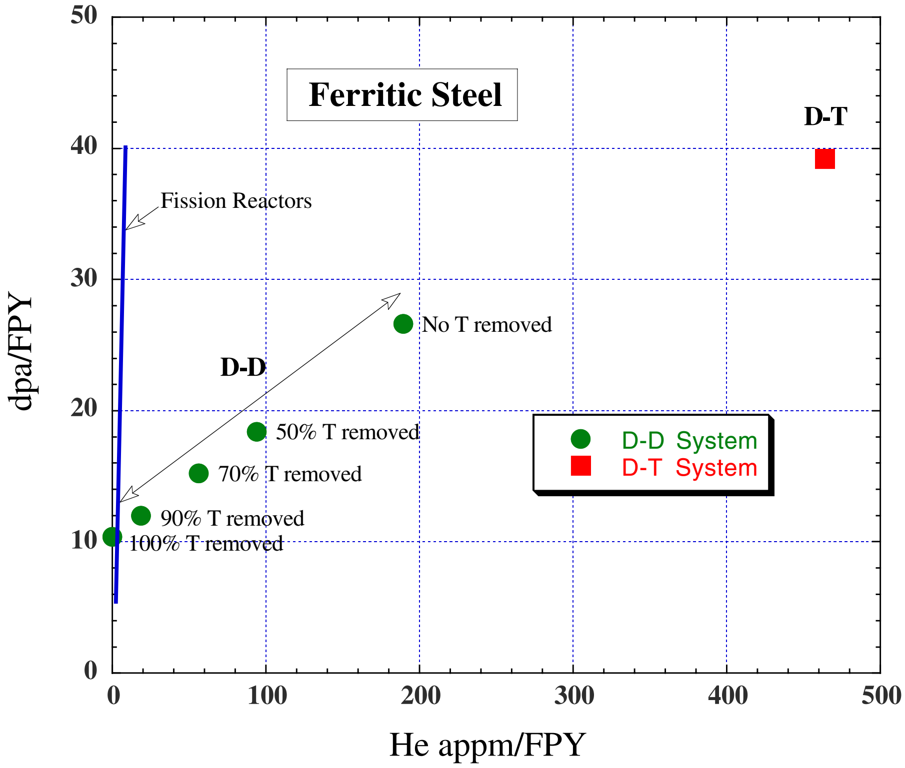

Figure 10. dpa and He production rates in ferritic steel for D-T and D-D systems.

production, and burnup rates. Figure 10 shows the dpa and He production rates relative to each other as one moves from a D-T system to equivalent D-D systems. The range of dpa and He production for FS alloys in fission reactors is indicated in the figure. Rates up to 40 dpa/FPY and 8 He appm/FPY can be obtained in fission test reactors. Removing the produced tritium from the D-D system results in He production rates that approach values in fission test reactors.

For a fully catalyzed D-D system, the peak ferritic steel dpa, He production, H production, and burnup rates are 26.6 dpa/FPY, 189.3 He appm/FPY, 842.7 H appm/FPY, and 0.103% burnup/FPY, respectively. As the fraction of tritium removed is increased, the damage parameters decrease with the He production rate decreasing by more than three orders of magnitude when all the tritium is removed. The relative improvement is similar to that in the blanket concepts analyzed. Comparing the results to those with the FS/Li_2O/H_2O blanket, one notices that the impact of tritium removal and He-3 recycling on damage parameters in the ferritic steel FW is nearly identical in both cases. The reduction in damage parameters as one moves from the catalyzed D-D system to the case with all tritium being removed is slightly lower for a non-breeding shield compared to a breeding blanket. However, the difference is very small and the impact of the material used in the blanket/shield can be considered as a second-order effect.

8. Summary and conclusions

The fraction of fusion energy carried by neutrons in a D-D system is reduced significantly as the tritium produced by D-D fusion is removed so that it cannot fuse. Recycling the He-3 obtained from the decay of the removed tritium also results in additional reduction in the fraction of fusion energy carried by neutrons. The fraction of the 14.1 MeV component of the neutron spectrum reduces significantly as the tritium removal fraction increases. Neutronics calculations have been performed to determine the impact of removing tritium and recycling part of it as He-3 in a D-D system on the peak structure damage parameters. The results were compared to those in a D-T system with the same fusion power wall loading. The structural materials considered are vanadium alloy V4Cr4Ti, ferritic steel alloy 9Cr-2WVTa, and SiC/SiC composite. The relative effects were found to be similar for the different structural materials.

For a catalyzed D-D system (no tritium removal), the peak dpa rate in the structural material is 25-35% lower than that in the equivalent D-T system. The gas production and transmutation rates are ~60% lower. As the fraction of tritium removed is increased, the damage parameters decrease with gas production and transmutations decreasing by more than two orders of magnitude with full tritium removal. On the other hand, the dpa rate decreases by a factor of 2.3-2.8. With ~75% tritium removal the gas production and transmutation rates are an order of magnitude lower than those in an equivalent D-T system. In this case, information from tests in fission reactor spectra will be useful in determining the lifetime. Although the dpa rate cannot be reduced by more than a factor of ~4 compared to the D-T system when all tritium is removed and recycled as He-3, the accompanying significant reduction in gas production can lead to a larger lifetime enhancement compared to that indicated by the modest reduction in the dpa rate. The effect of recycling the removed tritium as He-3 is at most a factor of ~1.7 reduction in the rates of damage parameters. Nevertheless, an additional factor of up to 1.7 reduction would be very important to overall blanket/shield lifetime.

In addition to enhancing the structural material lifetime, the safety and environmental characteristics will improve. The reduction of the amount of neutrons produced in the plasma and the energy spectrum softening lead to a significant reduction in the amount of generated short and long lived radioactive isotopes with improvement in safety issues related to accidental release of radioactive material, enhancement of accessibility for maintenance, and reduction of radwaste level. These effects will be investigated in future work.

Acknowledgement

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