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

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I. Introduction

The two branches of the D-D reaction produce He-3 and tritium. The only neutrons produced are low 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 fully 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. However, the significant amount of DT neutrons produced in a fully catalyzed D-D system, could lead to considerable structural radiation damage and gas production in the surrounding materials resulting in limiting the lifetime of the chamber components. By systematically lowering the amount of tritium allowed to burn in a D-D system, the fraction of fusion energy carried by DT neutrons is reduced [1]. The D-He-3 reaction produces a large amount of fusion energy that is carried only by charged particles. Hence, 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.

II. 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}). In such a system the fusion reactions are represented by the following equation that also indicates the energy carried by the produced neutrons and charged particles:

$$
\begin{aligned}
[4 + (1-f_{TR}) + (1+f_{Rec}\, f_{TR})]\, D \Rightarrow\ & T\ (1.01\ \text{MeV}) + p\ (3.02\ \text{MeV}) + \\
& {}^{3}He\ (0.82\ \text{MeV}) + n\ (2.45\ \text{MeV}) + \\
& [1-f_{TR}]\ {}^{4}He\ (3.5\ \text{MeV}) + [1-f_{TR}]\ n\ (14.1\ \text{MeV}) + \\
& [1+f_{Rec}\, f_{TR}]\ {}^{4}He\ (3.6\ \text{MeV}) + [1+f_{Rec}\, f_{TR}]\ p\ (14.7\ \text{MeV}).
\end{aligned}
$$

Based on this, the fraction of fusion energy carried by DD neutrons (2.45 MeV) is given by $2.45/[43.2-17.6f_{TR}+18.3f_{Rec}\, f_{TR}]$ and the fraction carried by DT neutrons (14.1 MeV) is $14.1(1-f_{TR})/[43.2-17.6f_{TR}+18.3f_{Rec}\, f_{TR}]$.

Table 1 gives the fraction of fusion power carried by neutrons as a function of the fraction of tritium removed for the case when all the tritium removed is recycled as He-3. Figures 1 and 2 show the fractions of fusion energy carried by DD and DT neutrons, respectively for three values of the fraction recycled as He-3. It is clear that the fraction of energy carried by DT neutrons is reduced significantly as one moves from a fully catalyzed D-D system (f_{TR}= 0) to a system with a large amount of tritium being removed. This reduction is attributed to the large decrease in the amount of D-T reactions taking place. On the other hand, the fraction of energy carried by the DD neutrons does not change or slightly increases (depending on the amount of He-3 recycling) as the tritium removal fraction increases due to the decreased total fusion energy. Figure 3 shows the fraction of fusion energy carried by all neutrons. It is clear that a significant reduction in energy carried by neutrons is achieved by increasing the fraction of tritium removed. Recycling the He-3 obtained from the decay of the removed tritium results also in reducing the fraction of fusion energy carried by neutrons. However, this effect is not as pronounced as that of removing the tritium from the plasma.

Table 1. Fraction of fusion power carried by neutrons as a function of fraction of tritium removed for the case when all the tritium removed is recycled as He-3.

Fraction of tritium removed	Fraction of fusion power carried by DD neutrons	Fraction of fusion power carried by DT neutrons	Fraction of fusion power carried by neutrons
0.0	0.0567	0.3264	0.3831
0.1	0.0566	0.2933	0.3499
0.2	0.0565	0.2603	0.3168
0.3	0.0564	0.2274	0.2838
0.4	0.0563	0.1946	0.2509
0.5	0.0563	0.1619	0.2181
0.6	0.0562	0.1293	0.1855
0.7	0.0561	0.0968	0.1529
0.8	0.0560	0.0644	0.1204
0.9	0.0559	0.0322	0.0881
1.0	0.0558	0.0000	0.0558

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 wall loading of 5 MW/m^2 from both neutrons and charged particles. Figure 4 shows the neutron wall loading values in the equivalent D-D system as a function of the fraction of tritium removed for the case when all tritium removed is recycled as He-3. It is clear that much lower neutron wall loadings are achieved compared to the D-T system. Notice that we assume that the D-D system will have the same size as the D-T system. However, D-D systems are expected to be relatively larger than D-T systems leading to an additional reduction in neutron wall loading. Figure 5 illustrates the impact of tritium removal on the energy spectrum of generated neutrons. The fraction of the 14.1 MeV component of the spectrum reduces significantly as the tritium removal fraction increases. For a fully catalyzed D-D system, half of the neutrons are at 14.1 MeV and the other half at 2.45 MeV. With complete tritium removal, all the neutrons are at 2.45 MeV. Since the D-He-3 reaction does not produce any neutrons, He-3 recycling does not impact the neutron energy spectrum. It only results in decreasing the total number of neutrons produced for the same fusion power.

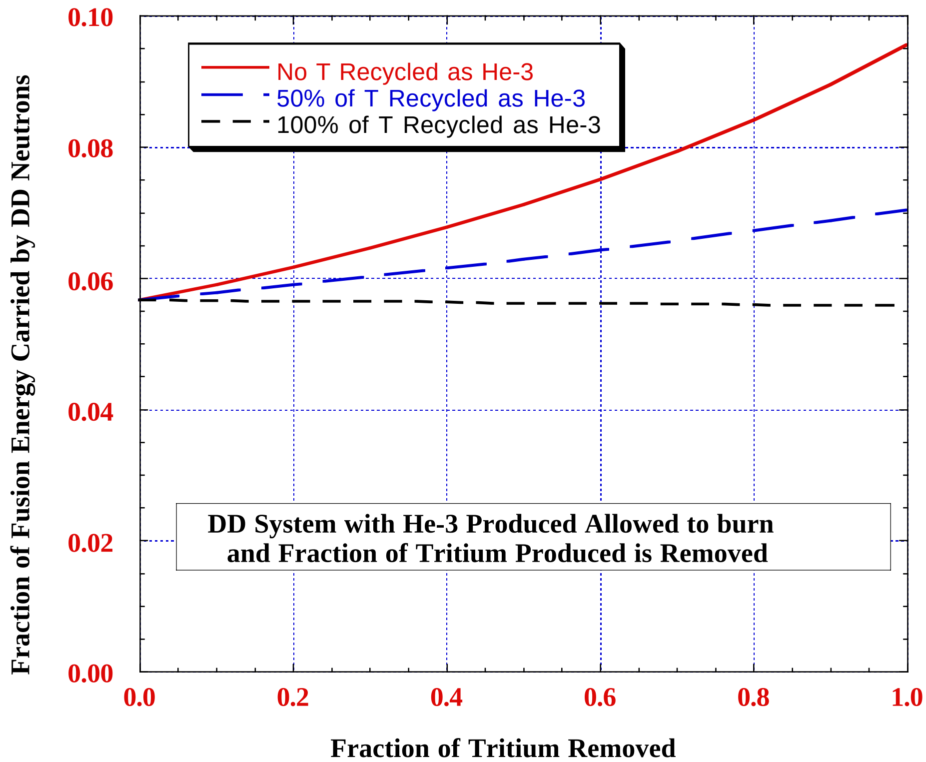

Figure 1. Impact on fraction of fusion energy carried by DD neutrons.

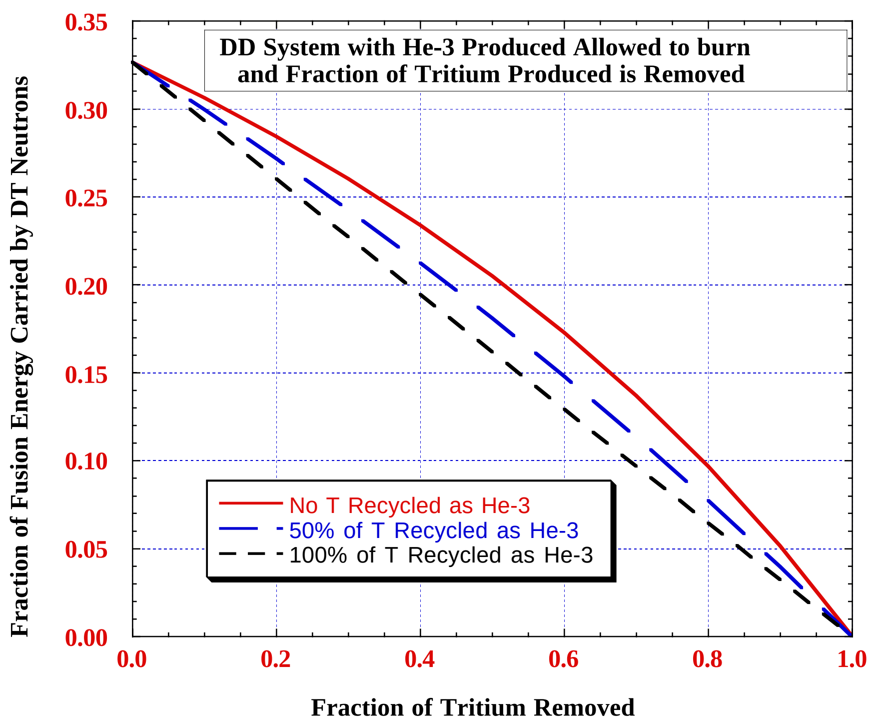

Figure 2. Impact on fraction of fusion energy carried by DT neutrons.

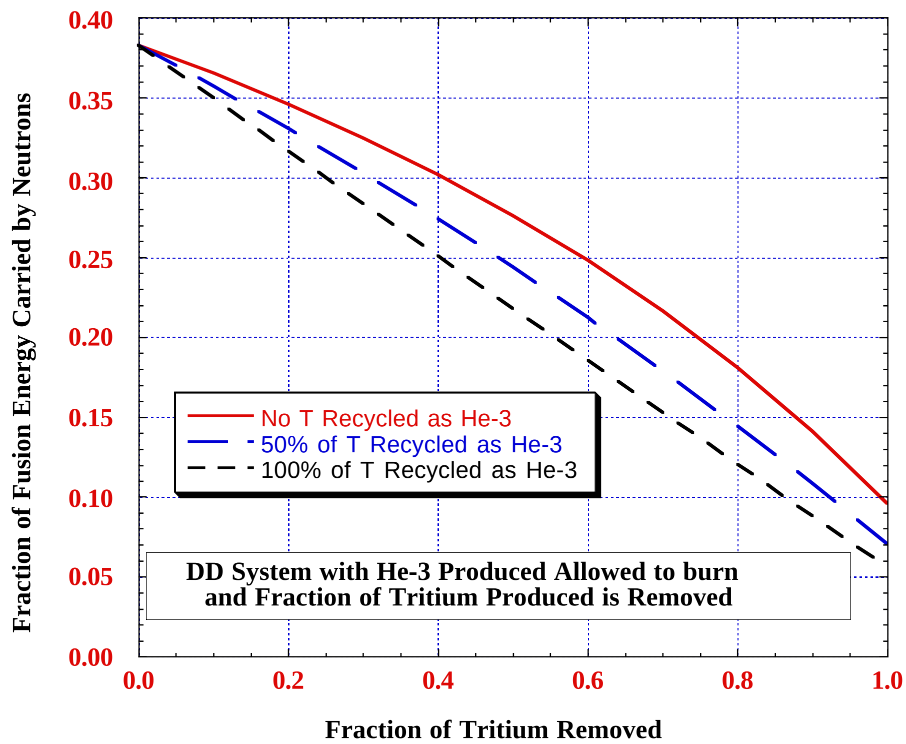

Figure 3. Impact on fraction of fusion energy carried by neutrons.

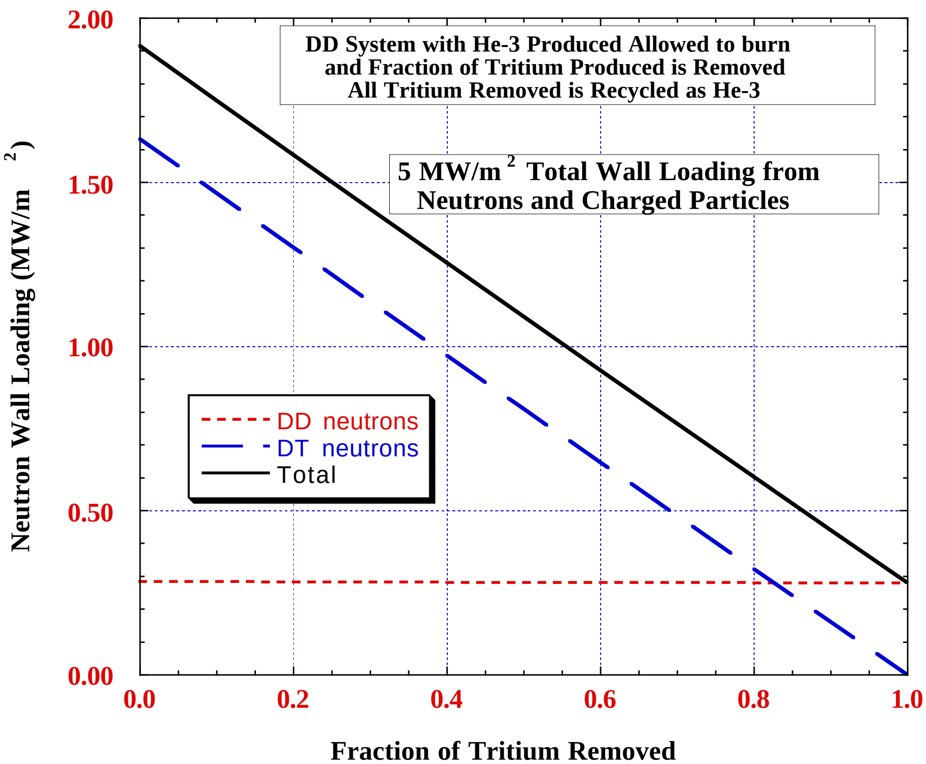

Figure 4. Neutron wall loading in D-D systems with same fusion power and size as a D-T system with 4 MW/m^2 neutron wall loading.

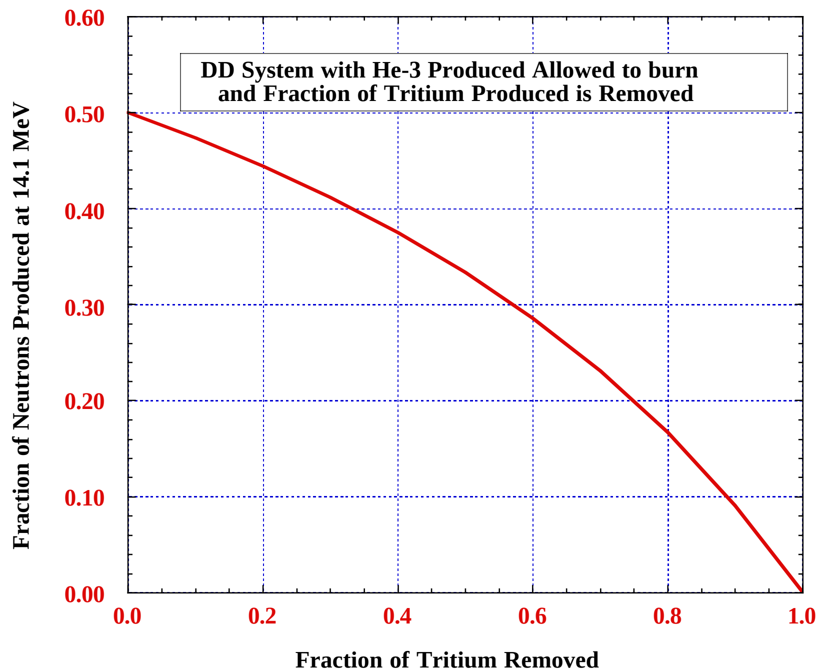

Figure 5. Fraction of neutron energy spectrum at 14.1 MeV.

III. Calculation Procedure

One-dimensional calculations have been performed to determine the impact of removing tritium and recycling part of it as He-3 in a D-D system. The fraction of tritium removed from the D-D plasma was varied from 0 to 100%. For each case, the calculations were performed for three options of the fraction of removed tritium that is recycled as He-3. These options are no He-3 is recycled, half of the tritium removed is recycled as He-3, and all of the tritium removed is recycled as He-3. The total energy flux from neutrons and charged particles at the first wall (FW) was kept at 5 MW/m^2 in all the cases analyzed. This corresponds to a neutron wall loading of 4 MW/m^2 in the equivalent D-T system. This corresponds to keeping the total fusion power and size the same in both D-T and D-D sytems. The neutron wall loading values and neutron energy spectra used in the calculations are given in Figures 4 and 5, respectively.

The material candidates considered for use as structural materials in fusion first wall/blanket/shield systems were analyzed. These are the vanadium alloy V4Cr4Ti, the ferritic steel alloy 9Cr-2WVTa, and the SiC/SiC composite. Neutrons scattered back from the blanket behind the FW will impact the neutron flux and spectrum at the FW. Therefore, although we are interested mainly in the peak damage parameters occuring in the FW material, the blanket should be included in the calculation model. Three of the candidate breeding blankets were considered that cover the different breeders and coolants considered in fusion systems. The blanket concepts considered are LiPb cooled SiC/SiC, Li cooled vanadium alloy, and water cooled ferritic steel (FS) with ceramic breeder. The Li_2O ceramic breeder was considered in the analysis. 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 which can be recycled in the D-D plasma or used in other D-He-3 systems. In order to isolate the effect of reduced neutron power and softer neutron spectra, we compared the damage parameters using the same blanket concept in D-T and D-D systems with different tritium removal and He-3 recycling. Replacing the tritium breeding blanket which has poor shielding features by a more effective shield offers several advantages. The radial build can be reduced significantly resulting in a smaller and lower cost system. That is in addition to eliminating the need for a tritium handling and extraction system for the blanket and reducing the blanket tritium inventory. To assess the combined effect of fuel cycle and elimination of breeding blanket we determined the peak radiation damage parameters for a water cooled ferritic steel 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 [2] was used to perform the calculations. The most recent version of the International Fusion Energy Nuclear Data Library, FENDL-2 [3], was utilized in a 175 neutron energy group structure. 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 [4]. For the SiC/SiC composite, the average displacement energies for the Si and C sublattices were taken to be 40 and 20 eV, respectively [5].

The FW/blanket/shield was modeled in cylindrical geometry with a 1 cm thick FW made of the structural material followed by a 1 m thick blanket/shield. Since our primary interest is in the damage parameters in the FW, the model did not include the vacuum vessel and magnet. The LiPb/SiC blanket consists of 90% LiPb and 10% SiC/SiC. The Li/V blanket is made of 90% Li and 10% V4Cr4Ti. The FS/Li_2O/H_2O blanket includes 10% 9Cr-2WVTa ferritic steel, 80% Li_2O and 10% H_2O. The water cooled steel shield consists of 90% 9Cr-2WVTa ferritic steel and 10% H_2O.

IV. Results for Li/V Blanket Concept

The calculations were performed for the Li/V blanket in D-T and D-D systems. The peak damage parameters at the first wall were compared. In the D-T system, the peak first wall dpa, helium production, hydrogen 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. Table 2 gives the FW damage parameter rates in the vanadium alloy for different tritium removal and He-3 recycling fractions. Figure 6 shows the values of these damage parameters in D-D system relative to the values in an equivalent D-T system. The results are given as a function of the fraction of tritium removed. All the tritium removed is assumed to be recycled as He-3. For a catalyzed D-D system (no tritium removal), the peak dpa rate in the vanadium alloy is 30% lower than that in the equivalent D-T system. The gas production and transmutation rates are 60% lower than in the D-T system. Figure 7 illustrates 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 FFTF. 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.

As the fraction of tritium removed is increased, the damage parameters decrease. The reduction is more pronounced for gas production and transmutations which are produced by high energy threshold reactions. These parameters decrease by about two orders of magnitude with full tritium removal. On the other hand, the dpa rate decreases by only a factor of 2.5. The He/dpa ratio drops below one when more than 75% of the tritium is removed. In this case, the gas production and transmutation rates are an order of magnitude lower than those in an equivalent D-T system and lifetime of the structural material will not be influenced primarily by issues related to gas production such as He embrittlement and cavity swelling. It 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 even if all the tritium is removed and recycled as He-3 in the D-D system, the accompanying significant reduction in gas production can lead to a larger lifetime enhancement compared to that indicated by the reduction in the dpa rate.

The effect of changing the fraction of tritium removed that is recycled as He-3 is illustrated in Figures 8 and 9. The effect is more pronounced when a large amount 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.

Table 2. Rates of damage parameters in the vanadium alloy FW for different tritium removal and He-3 recycling fractions.

Fraction of tritium removed	Fraction of removed T recycled as He-3	dpa/FPY	He appm/FPY	H appm/FPY	% burnup/FPY
0.0	1.0	31.4	73.2	403.3	0.0476
0.5	1.0	21.9	36.7	201.1	0.0238
0.7	1.0	18.2	22.3	121.2	0.0143
0.8	1.0	16.3	15.1	81.3	0.0096
0.9	1.0	14.4	7.9	41.7	0.0049
1.0	1.0	12.6	0.8	2.2	0.0003
0.0	0.5	31.4	73.2	403.3	0.0476
0.5	0.5	24.4	41.0	224.8	0.0265
0.7	0.5	21.2	26.1	141.8	0.0168
0.8	0.5	19.6	18.1	97.9	0.0116
0.9	0.5	17.8	9.7	51.4	0.0061
1.0	0.5	15.9	0.9	2.8	0.0004
0.0	0.0	31.4	73.2	403.3	0.0476
0.5	0.0	27.7	46.5	254.8	0.0301
0.7	0.0	25.6	31.5	171.3	0.0203
0.8	0.0	24.5	22.6	122.4	0.0145
0.9	0.0	23.1	12.7	66.9	0.0080
1.0	0.0	21.6	1.3	3.8	0.0005

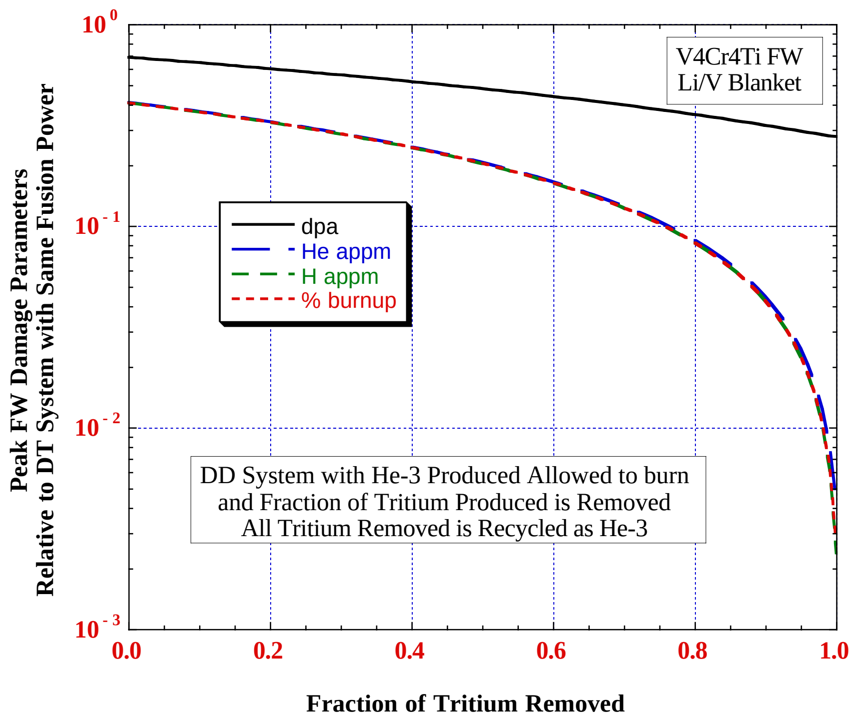

Figure 6. Peak damage parameters in vanadium as a function of tritium removal fraction in D-D a system.

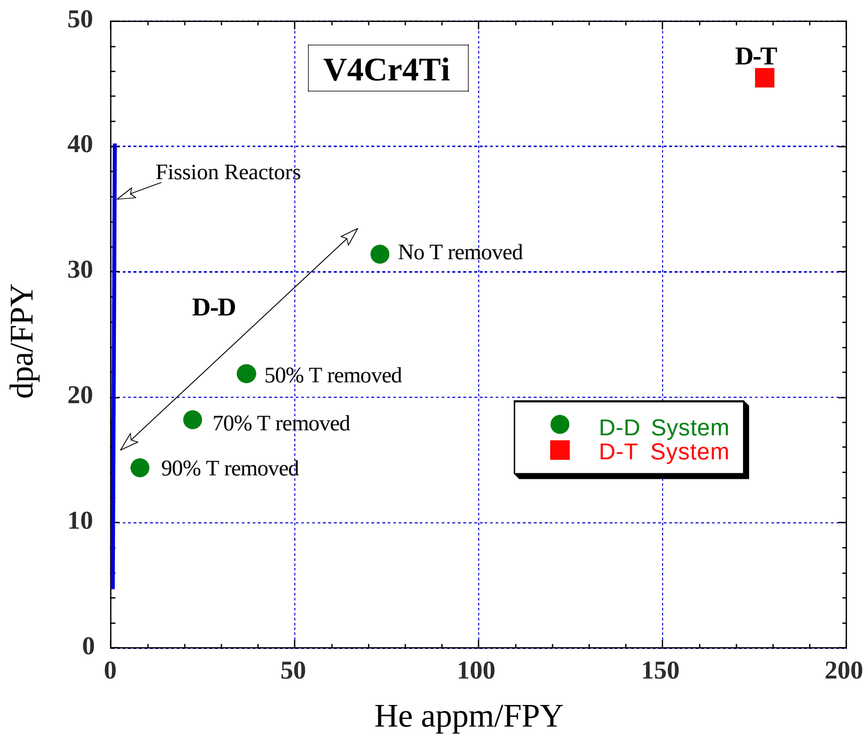

Figure 7. dpa and He production rates in vanadium for equivalent D-T and D-D systems.

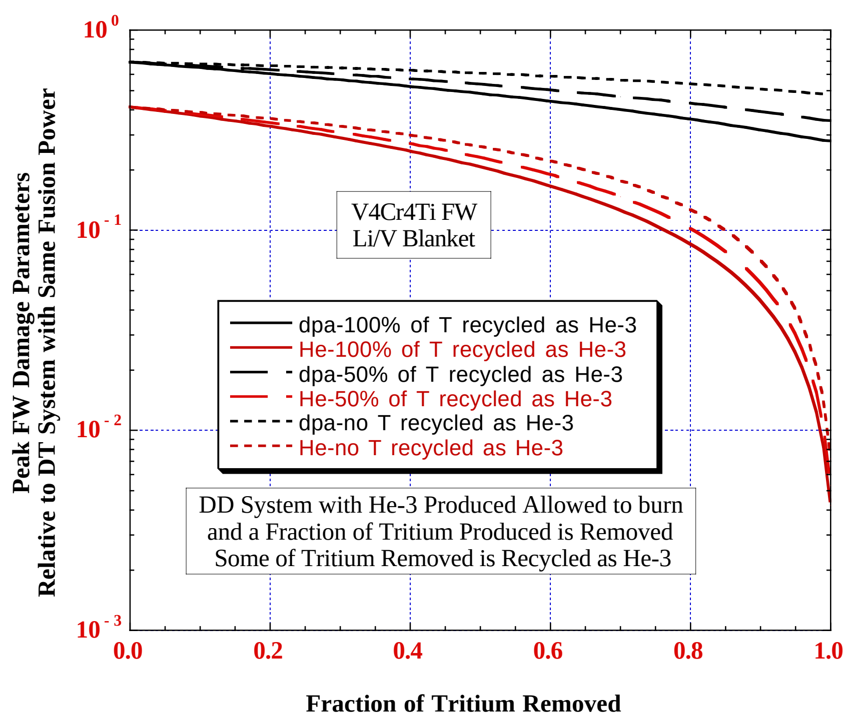

Figure 8. Peak dpa and He production in vanadium as a function of tritium removal fraction and He-3 recycling in D-D system.

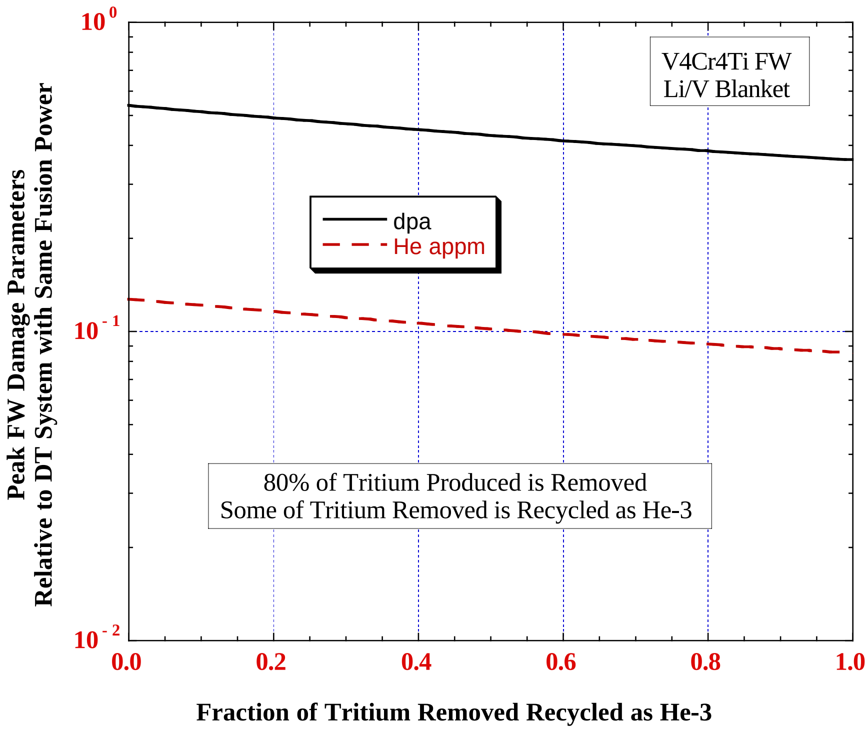

Figure 9. Impact of recycling fraction on dpa and He production in vanadium with 80% of tritium removed in a D-D system.

V. Results for LiPb/SiC Blanket

Calculations were performed for a blanket design concept that is made of SiC/SiC composite and is self-cooled by LiPb. The peak damage parameters at the first wall were determined for both the carbon and silicon sublattices of the SiC/SiC composite structure. In the D-T system, the peak dpa, helium production, hydrogem 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, 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 in which only one C atom is burned for every three helium atoms generated. 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.

We performed calculations in a D-D system with different tritium removal and He-3 recycling fractions. Table 3 gives the peak first wall dpa, helium production, hydrogen production, and burnup rates in both sublattices as a function of the fraction of tritium removed. All the tritium removed is assumed to be recycled as He-3. The results are shown in Figure 10. For a catalyzed D-D system (no tritium removal), the peak dpa rates are about 25% lower than those in the equivalent D-T system. On the other hand, the gas production rates and burnup rates are 60% lower than in the D-T system. These relative improvements are almost identical to those obtained for the V4Cr4Ti alloy. Figure 11 shows the average dpa and He production rates in SiC relative to each other. The average displacement energy for SiC was taken to be 25 eV [5]. The range of dpa and He production for SiC in fission reactors is indicated in the figure. Rates up to 40 dpa/FPY and 200 He appm/FPY are obtained in FFTF. 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 relative rates for dpa and burnup for both of the C and Si sublattices are depicted in Figure 12.

As the fraction of tritium removed is increased, the damage parameters decrease. The reduction is more pronounced for gas production and transmutations. The dpa rate decreases by a factor of ~2.3 for both sublattices with full tritium removal. On the other hand, 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. With full tritium removal all neutrons are at 2.45 MeV which is below the threshold energy for most of the gas producing reactions. The He/dpa ratio drops below one when more than 95% of the tritium is removed. Again, as in the case of the vanadium alloy, the He and H production rates as well as burnup rate 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. This implies that if the lifetime of the SiC/SiC composite is influenced primarily by gas production or burnup, significant enhancement of lifetime can be achieved by removing >75% 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.

The effect of changing the fraction of tritium removed that is recycled as He-3 is similar to that observed for the Li/V concept. The effect is more pronounced when a large amount of tritium is removed. With 90% of the tritium being removed, the damage parameters are a factor of ~1.6 lower for the case when all the removed tritium is recycled as He-3 compared to the case without He-3 recycling. This is illustrated in Fig. 13 where the dpa and He production rates in the C sublattice are plotted as a function of the fraction recycled. Again, 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. However, the up to a factor of 1.6 enhancement in lifetime with He-3 recycling is still a significant improvement.

Table 3. Rates of damage parameters in C and Si sublattices as a function of the fraction of tritium removed with all removed tritium being recycled as He-3.

Fraction of tritium removed	dpa/FPY in C	dpa/FPY in Si	appm/FPY in C	He appm/FPY in Si	H appm/FPY in C	H appm/FPY in Si	% burnup/FPY in C	% burnup/FPY in Si
0.0	50.4	40.4	3442.9	873.8	0.67	1593.5	0.1210	0.2467
0.5	36.4	28.8	1707.1	433.3	0.33	792.9	0.0600	0.1226
0.7	30.9	24.2	1020.9	259.4	0.20	472.7	0.0360	0.0732
0.8	28.1	21.9	679.4	172.7	0.13	314.7	0.0240	0.0487
0.9	25.4	19.6	339.2	86.3	0.07	157.0	0.0120	0.0243
1.0	22.6	17.3	0.0	0.12	0.00	0.0	0.0000	0.0000

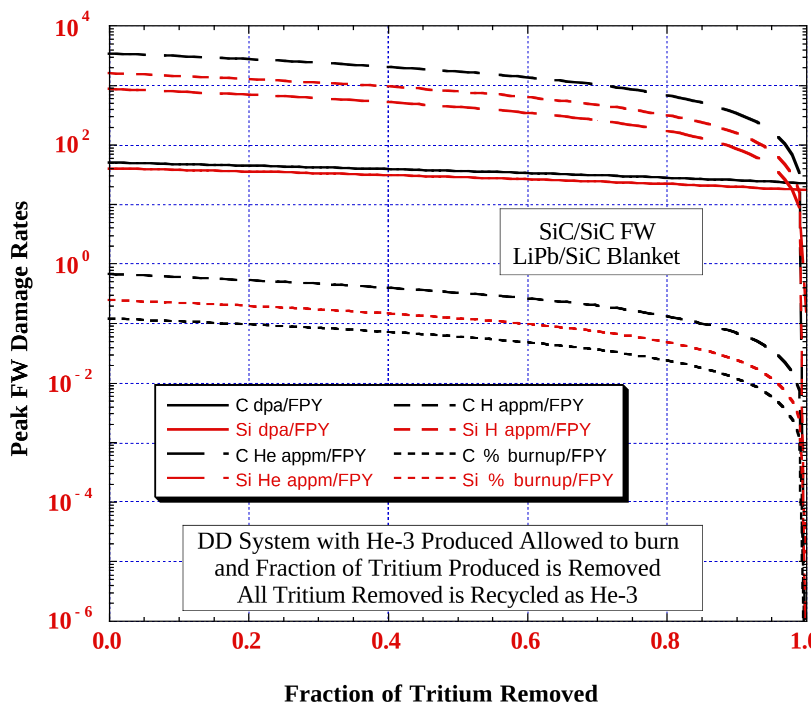

Figure 10. Peak damage rates in SiC/SiC composite as a function of tritium removal fraction in a D-D system.

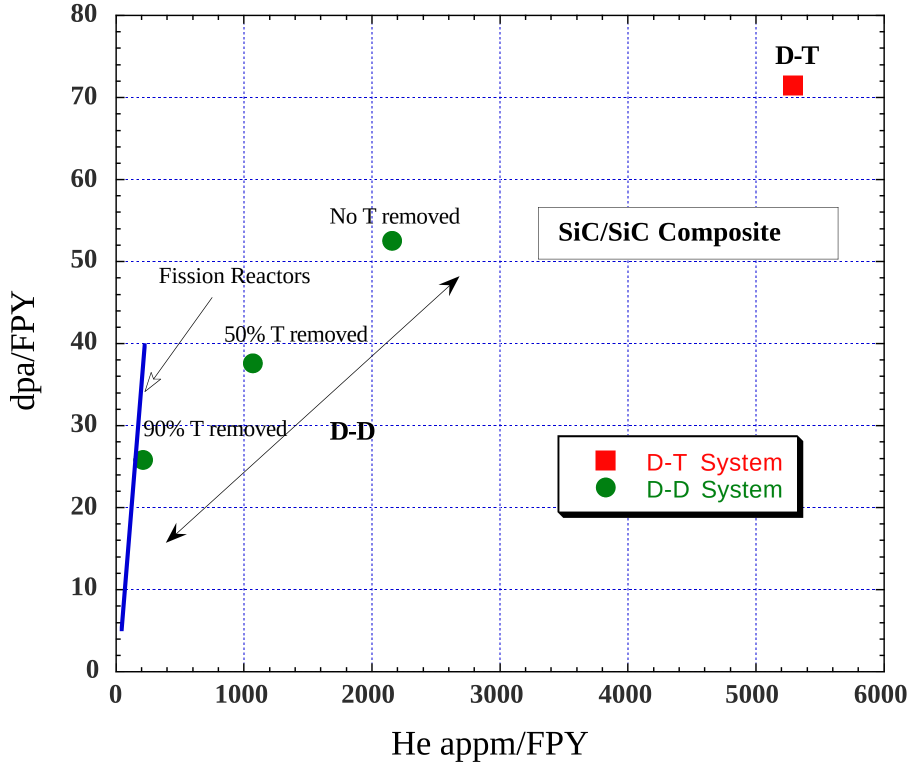

Figure 11. dpa and He production rates in SiC for equivalent D-T and D-D systems.

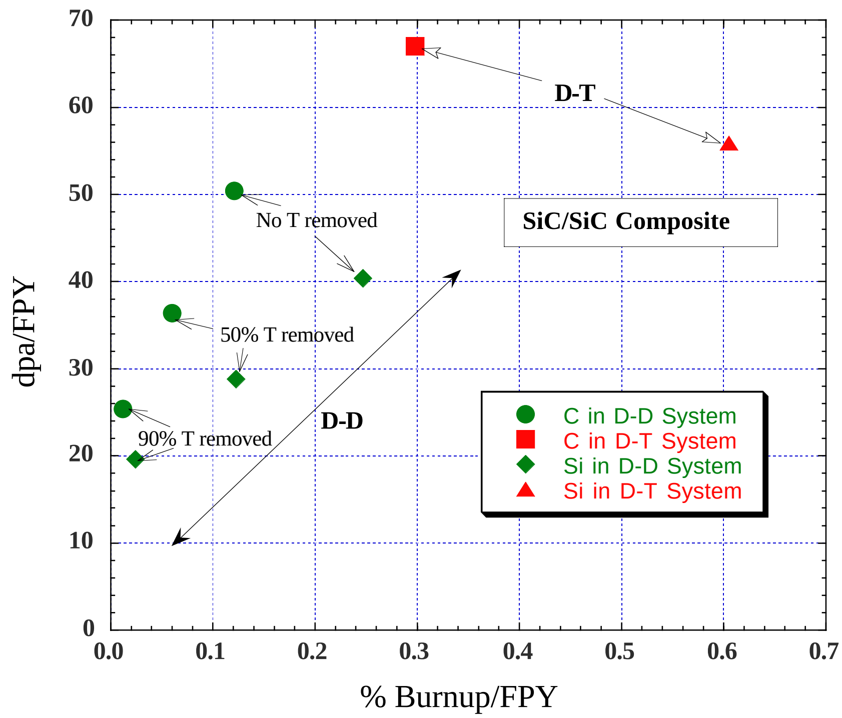

Figure 12. dpa and burnup rates in the C and Si sublattices of SiC/SiC composite for equivalent D-T and D-D systems.

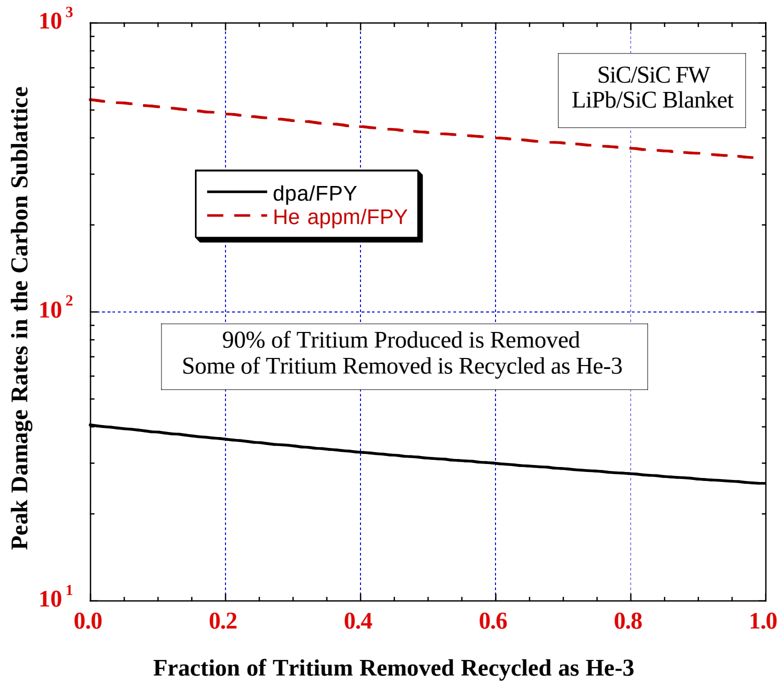

Figure 13. Impact of recycling fraction on dpa and He production rates in the C sublattice of SiC/SiC composite with 90% of tritium removed in a D-D system.

VI. Results for FS/Li_2O/H_2O Blanket Concept

The calculations were performed for the FS/Li_2O/H_2O blanket in D-T and D-D systems with different tritium removal and He-3 recycling fractions. The peak damage parameters at the first wall were compared. In the D-T system, the peak first wall dpa, helium production, hydrogen production, and burnup rates 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. Table 4 gives the rates of the damage parameters in the ferritic steel FW with all the tritium removed being recycled as He-3. Figure 14 shows the values of the damage parameters in a D-D system relative to the values in a D-T system as a function of the fraction of tritium removed. All the tritium removed is assumed to be recycled as He-3. For a catalyzed D-D system (no tritium removal), the peak dpa rate in the ferritic steel FW is 35% lower than that in the equivalent D-T system. The gas production and transmutation rates are ~60% lower than in the D-T system. Again these relative effects are similar to those obtained for the Li/V and LiPb/SiC blanket concepts.

As the fraction of tritium removed is increased, the damage parameters decrease. The reduction is more pronounced for gas production and transmutations which are produced by high energy threshold reactions. 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. The He/dpa ratio drops below one when more than 95% of the tritium is removed. The results imply that if lifetime of the ferritic steel is influenced primarily by gas production or transmutations, significant enhancement of lifetime can be achieved by removing the tritium and recycling it as He-3. 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 of the structural material. Although the dpa rate cannot be reduced by more than a factor of 4 compared to the D-T system even if all the tritium is removed and recycled as He-3 in the D-D system, the accompanying significant reduction in gas production can lead to larger a lifetime enhancement compared to that indicated by the reduction in the dpa rate.

The effect of changing the fraction of tritium removed that is recycled as He-3 is illustrated in Figures 15 and 16. The effect is more pronounced when a large amount 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. 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.

Table 4. Rates of damage parameters in ferritic steel FW of the FS/Li_2O/H_2O blanket concept as a function of the fraction of tritium removed with all removed tritium being recycled as He-3.

Fraction of tritium removed	dpa/FPY	He appm/FPY	H appm/FPY	% burnup/FPY
0.0	24.9	196.6	873.2	0.1070
0.5	16.9	97.7	439.6	0.0538
0.7	13.7	58.3	268.3	0.0327
0.8	12.2	38.8	183.2	0.0222
0.9	10.6	19.4	98.4	0.0118
1.0	9.0	0.038	13.8	0.0014

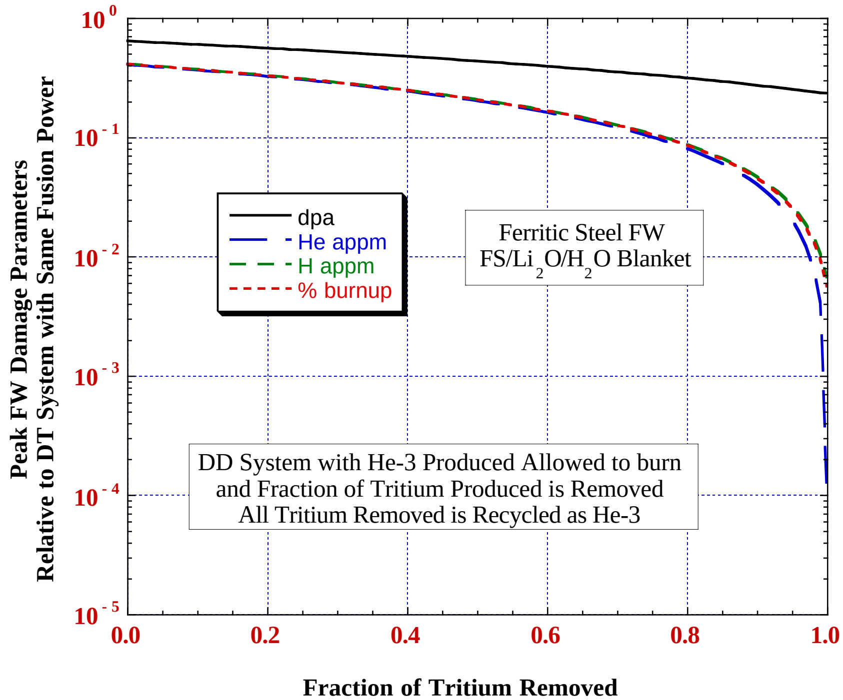

Figure 14. Peak damage parameters in ferritic steel as a function of tritium removal fraction in a D-D system.

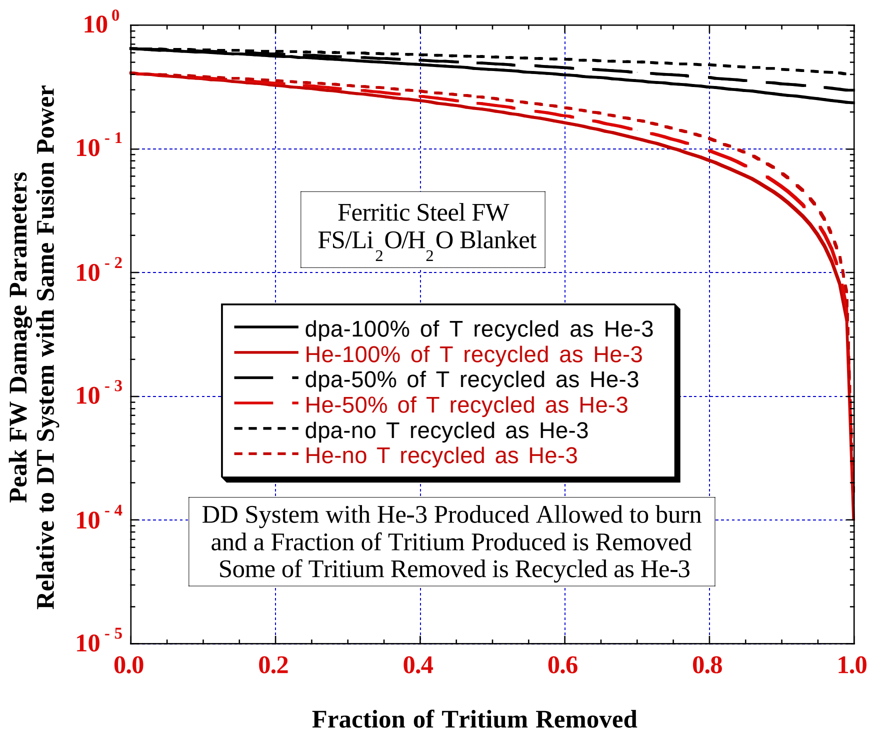

Figure 15. Peak dpa and He production in ferritic as a function of tritium removal fraction and He-3 recycling in a D-D system.

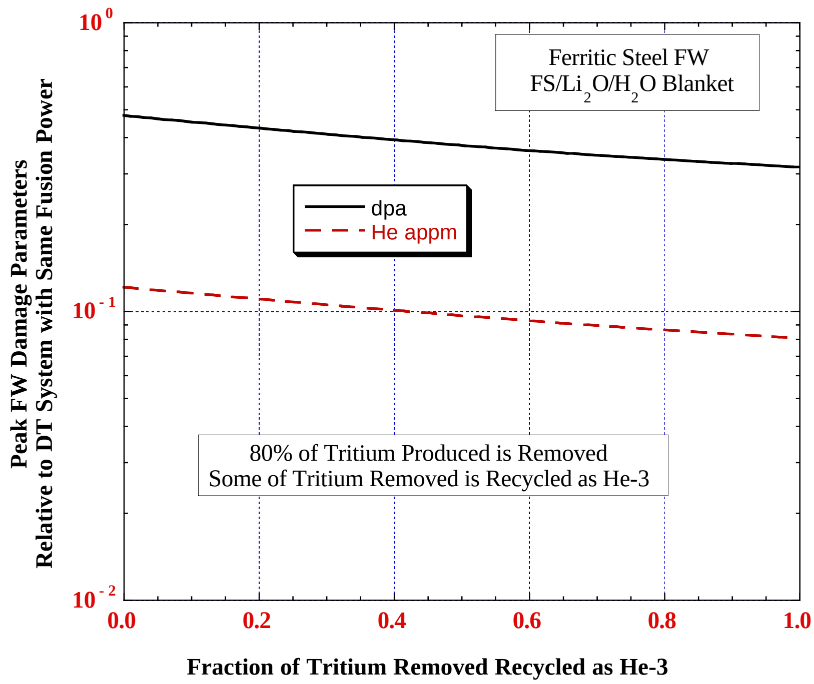

Figure 16. Impact of recycling fraction on dpa and He production in ferritic steel with 80% of tritium removed in a D-D system.

VII. 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. Table 5 lists the rates of damage parameters in the ferritic steel FW of the FS/water shield for different fractions of tritium removal and He-3 recycling. Figure 17 gives the peak first wall dpa, helium production, hydrogen production, and burnup rates as a function of the fraction of tritium removed. All the tritium removed is assumed to be recycled as He-3. Figure 18 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 FFTF. It is clear that removing the produced tritium from the D-D system results in dpa and He production rates that approach values in fast fission reactors. For a catalyzed D-D system (no tritium removal), the peak ferritic steel dpa, helium production, hydrogen 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. Transmutations of Fe yield Mn and Cr and the major alloying elements Cr and W transmute into V, Ti, Ta, and Hf. As the fraction of tritium removed is increased, the damage parameters decrease. The reduction is more pronounced for gas production and transmutations with the He production rate decreasing by more than three orders of magnitude when all the tritium is removed. On the other hand, the dpa rate decreases by only a factor of 2.5. Again the relative improvement is similar to that in the blanket concepts analyzed.

The effect of changing the fraction of tritium removed that is recycled as He-3 is illustrated in Figures 19 and 20. The effect is more pronounced when a large amount 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. This effect is similar to that obtained for the three 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 difference between the two designs is essentially replacing the Li_2O in the breeding blanket by ferritic steel. This results in changing the neutron energy spectrum at the FW. The effect is different for the 14.1 MeV and 2.45 MeV components of the source neutrons. Using steel in place of Li_2O results in larger slowing down (through inelastic scattering) and resonance absorption of high-energy DT neutrons. On the other hand, using Li_2O in place of steel increases absorption (in Li) and slowing down (by elastic scattering) of the low energy DD neutrons. With a low tritium removal fraction, where the neutron source is dominated by the 14.1 MeV component, the results showed that using a non-breeding shield yields <4% lower damage parameters at the FW compared to the case with Li_2O breeder. In the case when all the tritium is removed from the D-D system, all the source neutrons are at 2.45 MeV and the results show ~10% higher FW damage parameters with the non-breeding shield compared to the breeding blanket. Consequently, 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 as far as the lifetime of the ferritic steel FW is concerned.

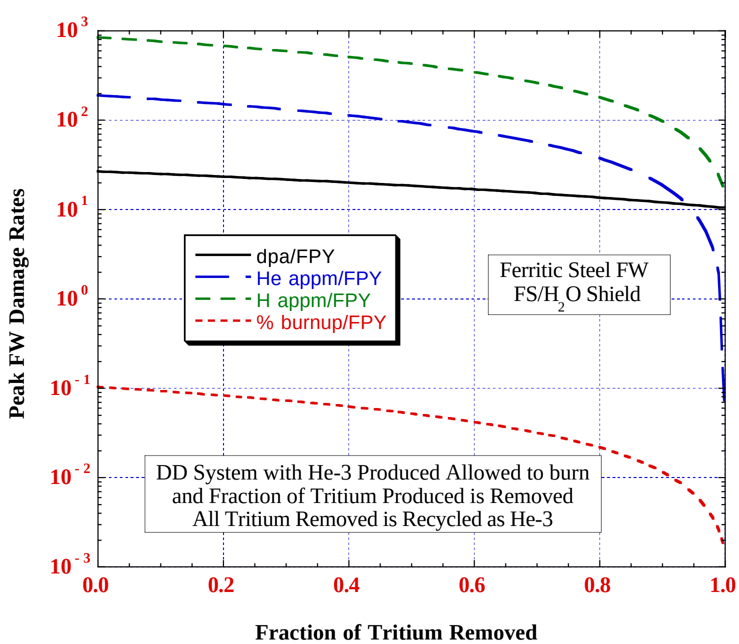

Figure 17. Peak damage rates in ferritic steel as a function of tritium removal fraction in a D-D system.

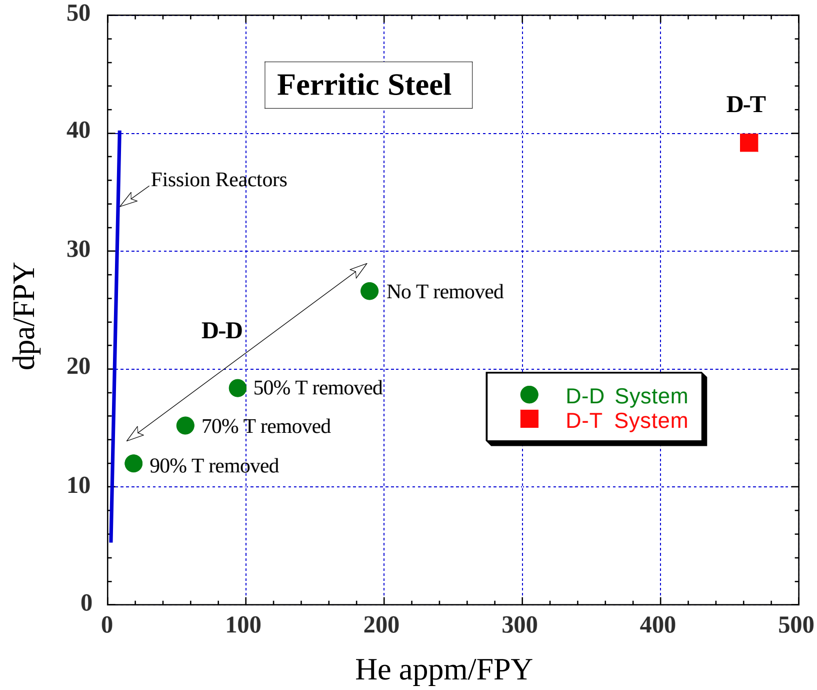

Figure 18. dpa and He production rates in ferritic steel for D-T and D-D systems.

Table 5. Rates of damage parameters in ferritic steel FW of the FS/water shield for different fractions of tritium removal and He-3 recycling.

Fraction of tritium removed	Fraction of removed T recycled as He-3	dpa/FPY	He appm/FPY	H appm/FPY	% burnup/FPY
0.0	1.0	26.6	189.3	842.7	0.1032
0.5	1.0	18.4	94.0	427.5	0.0522
0.7	1.0	15.2	56.2	261.4	0.0318
0.8	1.0	13.6	37.4	179.6	0.0217
0.9	1.0	12.0	18.7	97.1	0.0116
1.0	1.0	10.4	0.043	15.6	0.0016
0.0	0.5	26.6	189.3	842.7	0.1032
0.5	0.5	19.3	104.9	475.3	0.0580
0.7	0.5	17.8	65.9	306.7	0.0373
0.8	0.5	16.3	44.9	215.6	0.0261
0.9	0.5	14.8	23.0	119.7	0.0143
1.0	0.5	13.2	0.054	19.7	0.0020
0.0	0.0	26.6	189.3	842.7	0.1032
0.5	0.0	23.4	119.0	540.6	0.0660
0.7	0.0	21.5	79.4	370.4	0.0450
0.8	0.0	20.5	56.2	269.6	0.0326
0.9	0.0	19.3	29.9	156.0	0.0186
1.0	0.0	17.9	0.073	26.8	0.0027

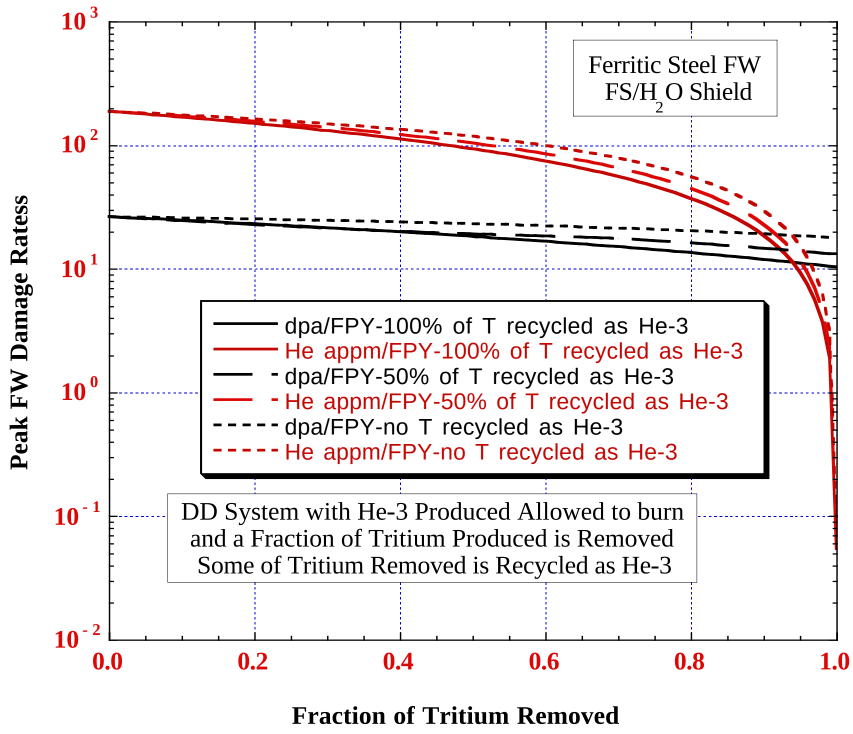

Figure 19. Peak dpa and He production rates in ferritic steel as a function of tritium removal fraction and He-3 recycling in a D-D system.

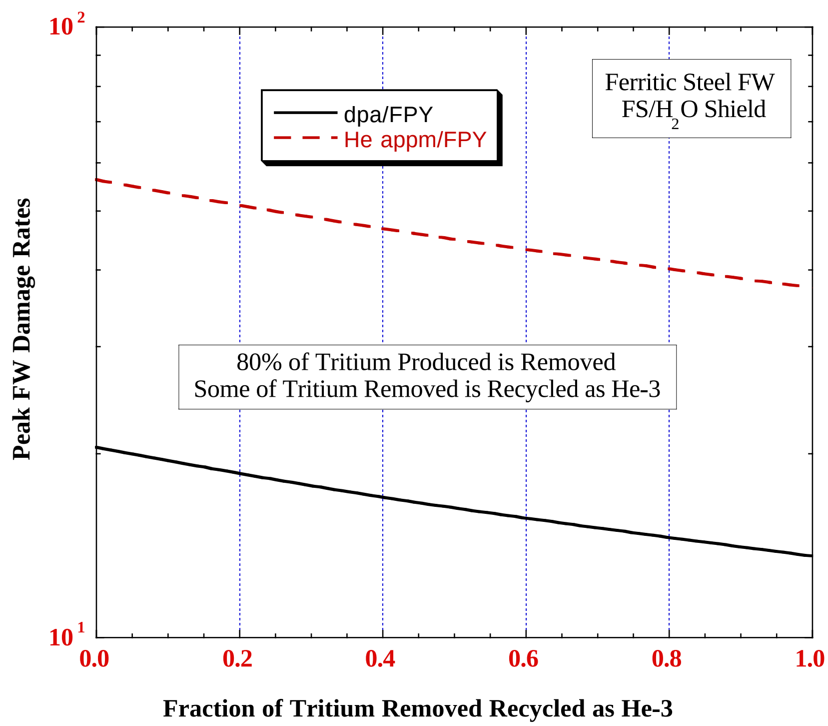

Figure 20. Impact of recycling fraction on dpa and He production rates in ferritic steel with 80% of tritium removed in a D-D system.

VIII. Summary and Conclusions

The fraction of fusion energy carried by neutrons is reduced significantly in a catalyzed D-D system 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. However, this effect is not as pronounced as that of removing the tritium from the plasma. The fraction of the 14.1 MeV component of the neutron spectrum reduces significantly as the tritium removal fraction increases. For a fully catalyzed D-D system, half of the neutrons are at 14.1 MeV. With complete tritium removal, all the neutrons are at 2.45 MeV.

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 in the first wall. The results were compared to those in an equivalent D-T system. The total fusion power and size were kept the same in both D-T and D-D systems. The Li/V, LiPb/SiC, and FS/Li_2O/H_2O breeding blanket concepts in addition to a non-breeding FS/H_2O shield were analyzed. The structural materials considered are the vanadium alloy V4Cr4Ti, the ferritic steel alloy 9Cr-2WVTa, and the SiC/SiC composite. The relative effects were found to be similar for the different structural materials with the impact of other materials used in the blanket/shield having only a second-order effect.

The results showed that 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 than in the D-T system. As the fraction of tritium removed is increased, the damage parameters decrease with the reduction being more pronounced for gas production and transmutations. These parameters decrease by more than two orders of magnitude with full tritium removal. On the other hand, the dpa rate decreases by only 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, the lifetime will not be influenced primarily by issues related to gas production and information from tests in fission reactor spectra will be useful in determining the lifetime of the structural material. Although the dpa rate cannot be reduced by more than a factor of ~4 compared to the D-T system even if all the tritium is removed and recycled as He-3 in the D-D system, the accompanying significant reduction in gas production can lead to a larger lifetime enhancement compared to that indicated by the reduction in the dpa rate. The results indicate that 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. Hence, the enhancement of the structure lifetime is more sensitive to the fraction of tritium removed than to the He-3 recycling fraction. 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, by systematically removing the produced tritium from the D-D system and recycling it after decay as He-3, 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 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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