Structural Materials Damage in Fusion and Fission Systems

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Abstract

Calculations were performed to quantify the damage parameters in the leading candidate structural and plasma facing materials when used in magnetic and inertial confinement fusion systems and when irradiated in fission reactors. The structural materials considered are ferritic steel, austenitic steel, vanadium alloy and SiC/SiC composite. Plasma facing materials included beryllium, tungsten, and carbon fiber composites. Atomic displacement damage and gas production rates are greatly influenced by the neutron energy spectrum. For the same neutron wall loading, atomic displacement damage is slightly lower in inertial fusion systems than in magnetic fusion systems but gas production is about a factor of 2 lower due to the softened neutron spectrum. In addition, much lower gas production is obtained in samples irradiated in fission reactors. The results help guide irradiation experiments in fission reactors to properly simulate the damage environment in fusion systems and facilitate extrapolating to the expected material performance in fusion systems.

I. Introduction

Various structural materials have been proposed for use in breeding blankets of fusion reactors. A crucial aspect of the development of structural materials for fusion applications is the evaluation of the effects of neutron irradiation on their mechanical and physical properties. Due to the lack of fusion test facilities that allow irradiating materials in fusion relevant environment to fluences expected in future Demo and power plants, irradiation tests for structural materials are currently performed in fission reactors such as the High Flux Isotope Reactor (HFIR) at ORNL [1]. However, atomic displacement damage and gas production rates in structural materials are greatly influenced by the neutron energy spectrum. In a D-T fusion system, the neutron energy spectrum in the first wall (FW) and front region of the blanket are significantly harder than in fission reactors. In addition, the radiation damage parameters depend on the materials used in the blanket design and whether a magnetic (MFE) or inertial (IFE) confinement system is utilized. To understand how to correlate and extrapolate results from irradiation in fission test reactors to the actual environment in fusion systems, we performed calculations to quantify the damage parameters in the leading structural material candidates when used in MFE and IFE systems and when irradiated in HFIR. The structural materials considered are the ferritic steel alloy F82H, austenitic steel SS316, the vanadium alloy V4Cr4Ti and the SiC/SiC composite. The radial variation of damage parameters in the blanket was determined for each structural material. In addition, the candidate plasma facing armor materials beryllium, tungsten, and carbon fiber composites (CFC) [2] were considered.

II. Calculation Approach

The PARTISN code [3] was used, along with the FENDL-2.1 [4] nuclear data library in 175 neutron-42 gamma energy groups, to calculate the time integrated damage parameters. For the MFE system, the ARIES-AT [5] configuration was used. The radial build at mid-plane was modeled in cylindrical geometry with the inboard (IB) and outboard (OB) regions modeled simultaneously. The major radius is 5.2 m and the FW radii at the IB and OB sides are 3.85 and 6.55 m, respectively. The OB blanket thickness used is 0.8 m while the IB blanket is only 0.4 m thick. A uniform 14.1 MeV neutron source is used in the plasma zone. The IFE blanket is nearly spherical with neutrons emitted from the target at the center of the chamber. In the IFE system, we used the same blanket radial build as that used for the OB region in the MFE system. The calculations were performed in spherical geometry with a point isotropic neutron source emitting neutrons with a softened target energy spectrum at the center of a 4.25 m radius chamber. The HAPL target spectrum [6] with an average energy of 12.3 MeV was used. A water-cooled

SS316 shield with 25% water is included behind the blanket regions in both MFE and IFE systems. The differences in source geometry and energy spectrum for MFE and IFE systems impact the damage parameters in the blanket structural materials. The neutron wall loadings in the IFE system and in the OB region of the MFE system were normalized to the same time-average value of 6 MW/m^2.

The dual coolant lithium lead (DCLL) blanket design [7] was used to calculate the damage parameters in the ferritic and austenitic steel structural materials. A homogenized mixture consisting of 70% LiPb (with 90% ^{6}Li enrichment), 5% SiC flow channel insert, 15% steel structure, and 10% helium coolant. The blanket with SiC/SiC composite utilizes 90% LiPb (with 90% ^{6}Li enrichment) and 10% SiC/SiC. For the vanadium alloy, a self-cooled blanket consisting of 90% natural liquid lithium and 10% V4Cr4Ti structure, was used. In all four designs considered, a separate 7 mm thick FW made of the structural material was modeled separately to determine the peak damage parameters. The damage parameters in candidate plasma facing materials (Be, W, and CFC) were determined by placing a 5 mm armor on the plasma side of the FW of the DCLL blanket that utilizes the ferritic steel alloy F82H as structural material.

In order to compare the damage parameters in the MFE and IFE blankets to those obtained for the structural and plasma facing materials when irradiated in HFIR, calculations were performed using the neutron spectrum used for material irradiation in the flux trap region of HFIR [8]. This spectrum is shown in Fig. 1 compared to the spectra at the FW of the DCLL blanket with F82H structure in the MFE and IFE systems. The spectra are normalized to a total neutron flux of 10^{15} n/cm^2s. It is clear that the neutron energy spectrum in HFIR is much softer than in fusion systems. The neutron energy spectrum in the IFE system is slightly softer than in MFE due to the neutron interactions with the compressed target materials leading to significant reduction of the 14 MeV peak. These interactions also result in a high energy tail that is about two orders of magnitude lower than the 14 MeV peak. The cumulative damage parameters in fusion systems were compared to those obtained by HFIR irradiation based on the same cumulative fast (E>0.1 MeV) neutron fluence.

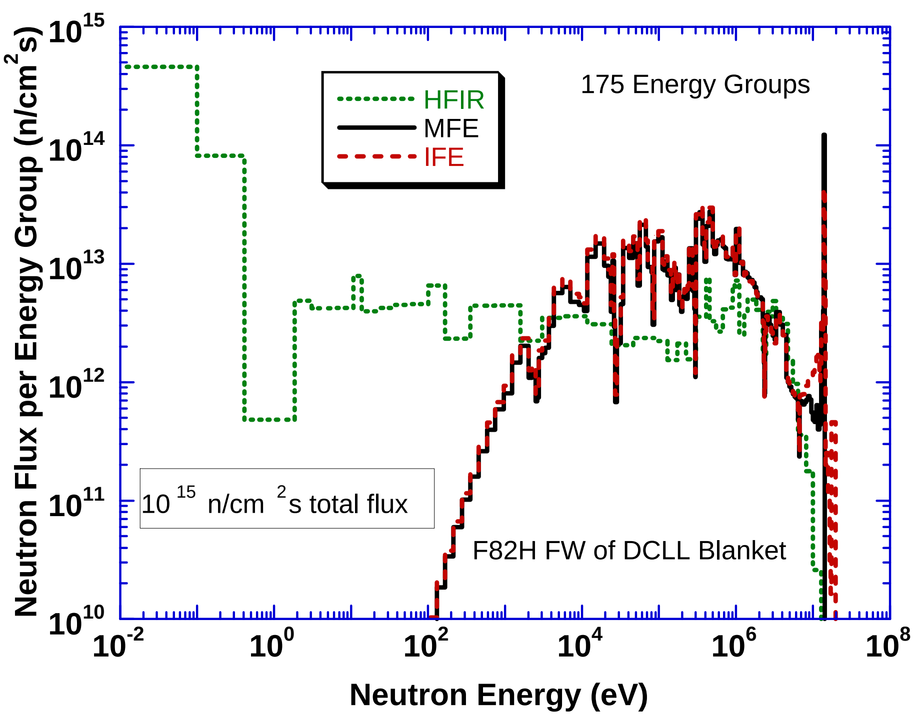

Figure 1. Neutron spectra at FW of DCLL blanket in MFE and IFE compared to HFIR.

III. DAMAGE PARAMETERS IN MFE AND IFE FUSION SYSTEMS

There are significant geometrical and spectral differences between MFE and IFE systems that affect the radiation damage levels with impact on lifetime assessment [9]. While a cylindrical or toroidal chamber surrounds a volumetric distributed source in MFE systems, a nearly spherical chamber surrounds a point neutron source in an IFE system. As a result, source neutrons in IFE chambers impinge on the FW/blanket in a more perpendicular direction. This leads to lower FW radiation damage parameters with a smaller radial gradient for the same neutron wall loading. The peak damage parameters in the FW are lower in IFE systems but start to be higher than in MFE systems at ~6 cm depth in the blanket. Thus, extrapolation of radiation damage parameters between MFE and IFE fusion energy systems is not possible.

Fusion neutron interactions in the compressed target result in considerable softening of the neutron spectrum incident on the FW/blanket in IFE chambers. While in MFE systems source neutrons incident on the FW are at 14.1 MeV, those incident on the FW of the IFE system have average energies in the range 10-13 MeV. In addition, some neutron multiplication takes place in the target. For each fusion reaction in the HAPL target, 1.05 neutrons are emitted from the target with an average energy of 12.3 MeV. For the same neutron wall loading, the lower average energy of source neutrons in IFE results in a larger number of neutrons impinging directly on the FW as compared to the MFE chamber. However, these lower energy neutrons produce less secondary neutrons from interactions in the blanket. The net result is comparable neutron fluxes at the FW. This softer spectrum, combined with the angular difference discussed above, contributes to the observed lower peak damage parameters at the FW in IFE systems.

Table I gives the peak atomic displacement damage (dpa), helium production, and hydrogen production per full power year (FPY) in the FW for the four candidate structural materials in the MFE and IFE systems for the same neutron wall loading of 6 MW/m^2. The results indicate that for the same neutron wall loading, the peak dpa values are lower in IFE systems than in MFE systems by ~27% for both ferritic and austenitic steel, 13% for SiC, and 37% for V4Cr4Ti. On the other hand, peak gas production in the IFE system is about a factor of two lower than in the MFE system. This reduction is much larger than that for dpa since the reactions leading to gas production have very high threshold energies. The results for the candidate plasma facing materials are given in Table II. Again, while the dpa values in the IFE reactor are slightly lower than in the MFE reactor, gas production is lower by about a factor of 2. The only exception is for hydrogen production in graphite due to the high threshold energy for (n,p) reaction in CFC (13.6 MeV) with increased contribution from the high-energy tail of the IFE spectrum above 14 MeV shown in Fig. 1.

TABLE I. PEAK DAMAGE PARAMETERS FOR STRUCTURAL MATERIALS IN MFE AND IFE SYSTEMS

Structural Material	dpa/FPY		He appm/FPY		H appm/FPY	
	MFE	IFE	MFE	IFE	MFE	IFE
F82H	86.6	63.4	843.5	416.1	3738	1852
SS316	89.7	65.9	904.7	461.5	4871	2505
SiC/SiC	109.3	95.1	9503	4538	3511	1739
V4Cr4Ti	80.7	51.0	333.6	155.3	1704	798.6

TABLE II. PEAK DAMAGE PARAMETERS FOR PLASMA FACING MATERIALS IN MFE AND IFE SYSTEMS

Plasma Facing Material	dpa/FPY		He appm/FPY		H appm/FPY	
	MFE	IFE	MFE	IFE	MFE	IFE
Be	44.3	44.1	18151	10972	287.1	131.5
W	27.2	19.5	13.4	6.5	49.8	24.1
CFC	74.0	70.7	14431	6959	2.9	4.9

Fig. 2 gives the dpa, helium production, and He/dpa ratio for the ferritic steel alloy F82H as a function of depth in the DCLL blanket when used in IFE and MFE reactors. Comparing these profiles indicated that the gradient for dpa and helium production is smaller in IFE than in MFE. This is a direct consequence of the geometrical differences discussed above. The peak damage parameters in the FW are lower in IFE systems but start to be higher than in a MFE system at ~6 cm depth in the blanket. The difference in gradient is more pronounced for helium production than for dpa leading also to a smaller gradient in the He/dpa ratio profile in the IFE system.

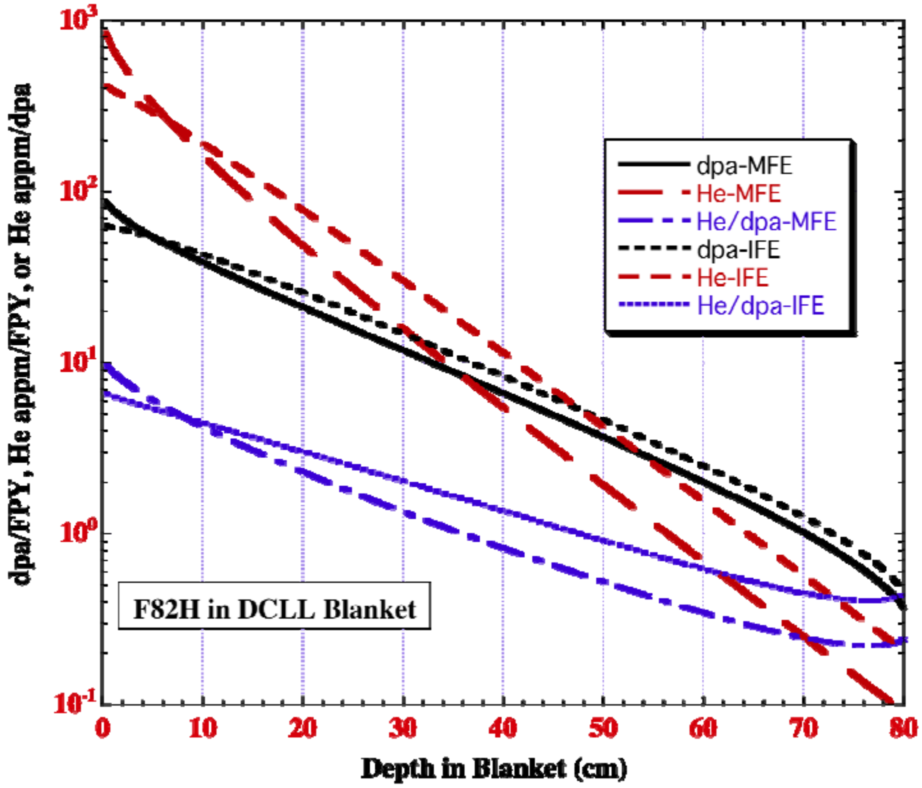

Figure 2. Comparison between F82H radial damage profiles in IFE ad MFE.

Fig. 3 compares the radial profiles of the He/dpa ratio for the four candidate structural materials in the OB blanket of the MFE reactor. At the FW, the values of the He/dpa ratio are significantly different for the different structural materials. While the ferritic and austenitic steel alloys have comparable values at the FW, SiC/SiC has about an order of magnitude higher value. This is attributed to the large helium production in the C sub-lattice resulting from the (n,n´3α) reaction [10]. The He/dpa ratio for V4Cr4Ti at the FW is about half that for steel due to the lower high-energy helium production cross sections. The 10 wppm B in the SS316 along with the large Ni content result in enhanced helium production as one moves deeper in the blanket with significant peaking at the back of the blanket close to the water-cooled shield with much softened neutron energy spectrum. It is clear that helium production in the back regions of the blanket is very sensitive to the boron content that should be reduced particularly if re-welding is required. The He/dpa ratio for V4Cr4Ti has only a modest drop as one moves deeper in the blanket because the lithium used in this blanket is not yielding significant neutron slowing down as that obtained in the other blankets with LiPb breeder/coolant.

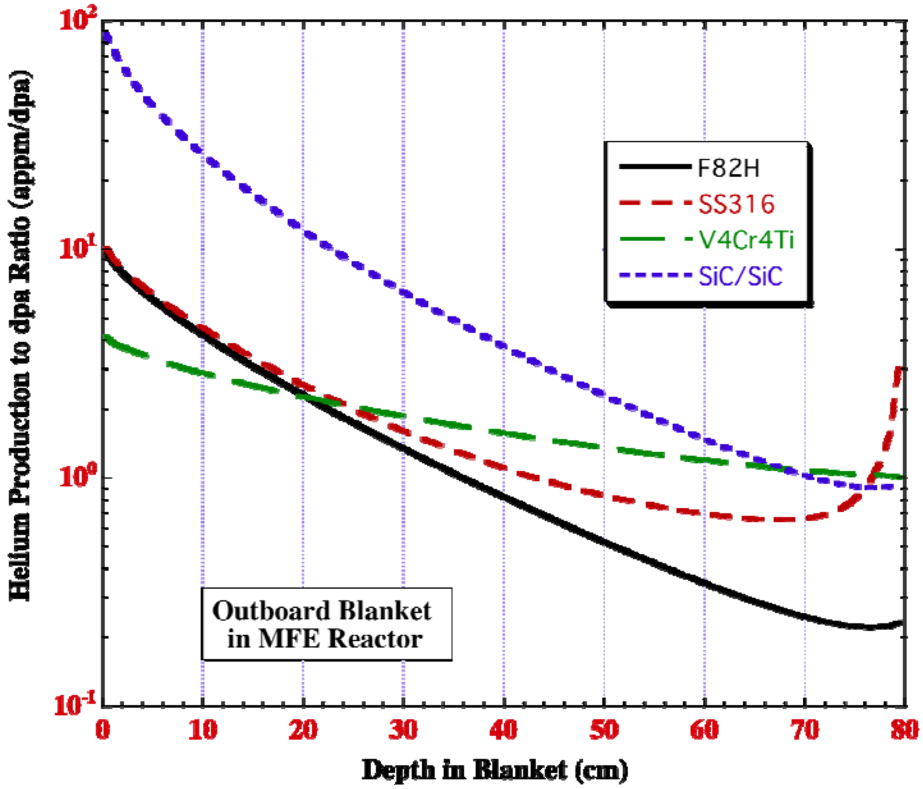

Figure 3. Radial variation of He/dpa ratio for candidate structural materials in OB MFE blanket.

IV. Damage Parameters in Fission and Fusion Environment

The neutron energy spectrum in fission reactors is significantly softer than in fusion systems as illustrated in Fig. 1. While ~75% of the neutrons are at energies >0.1 MeV at the FW of a fusion blanket, only 25% of the neutrons are at E>0.1 MeV in HFIR. For proper correlation of damage parameters in a fusion system to those from irradiation in a fission environment, the comparison was made based on the same fast neutron fluence (E>0.1 MeV) of 10^{23} n/cm^2. The results for the cumulative dpa and helium production at that fast neutron fluence are given in Table III for the candidate structural and plasma facing materials in MFE and IFE systems as well as in HFIR. The results are compared in Figs. 4 and 5 for the candidate structural materials. The atomic displacement damage in HFIR is comparable to that in fusion systems for the same fast neutron fluence. However, helium production is significantly different. It is much higher for SS316 following irradiation in HFIR due to the enhanced helium production by low energy neutrons in B and Ni. Helium production in Be is comparable in fission and fusion environment because of the relatively low threshold energy for reactions producing helium. For the same fast neutron fluence, helium production is much lower following HFIR irradiation of F82H, SiC/SiC, V4Cr4Ti, W, and CFC which have high threshold energies for reactions producing helium.

TABLE III. DPA AND HE PRODUCTION IN FUSION SYSTEMS AND HFIR FOR THE SAME FAST NEUTRON FLUENCE

Material	dpa			He appm		
	MFE	IFE	HFIR	MFE	IFE	HFIR
F82H	83.1	65.9	70.7	809.8	432.7	22.1
SS316	87.9	69.9	75.6	886.6	489.2	15300
SiC/SiC	110.4	102.7	110.4	9598	4901	168.4
V4Cr4Ti	142.8	116.8	96.7	590.5	355.6	4.6
Be	42.5	45.9	53.5	17425	11411	17829
W	26.1	20.3	19.5	12.9	6.8	0.02
CFC	71.0	73.5	73.1	13854	7237	129

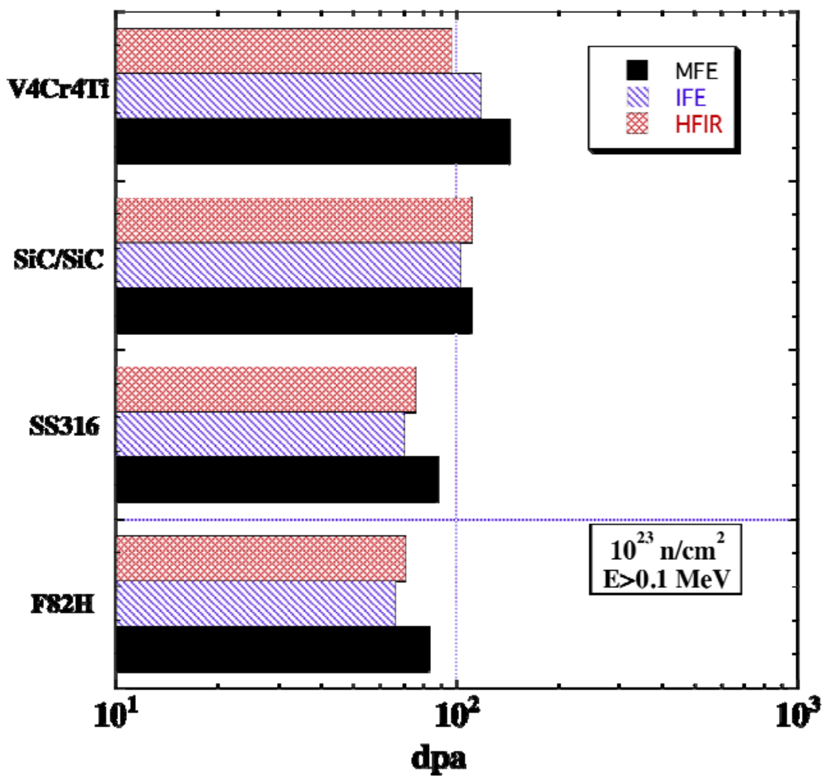

Figure 4. Structural material dpa comparison in fission and fusion environment.

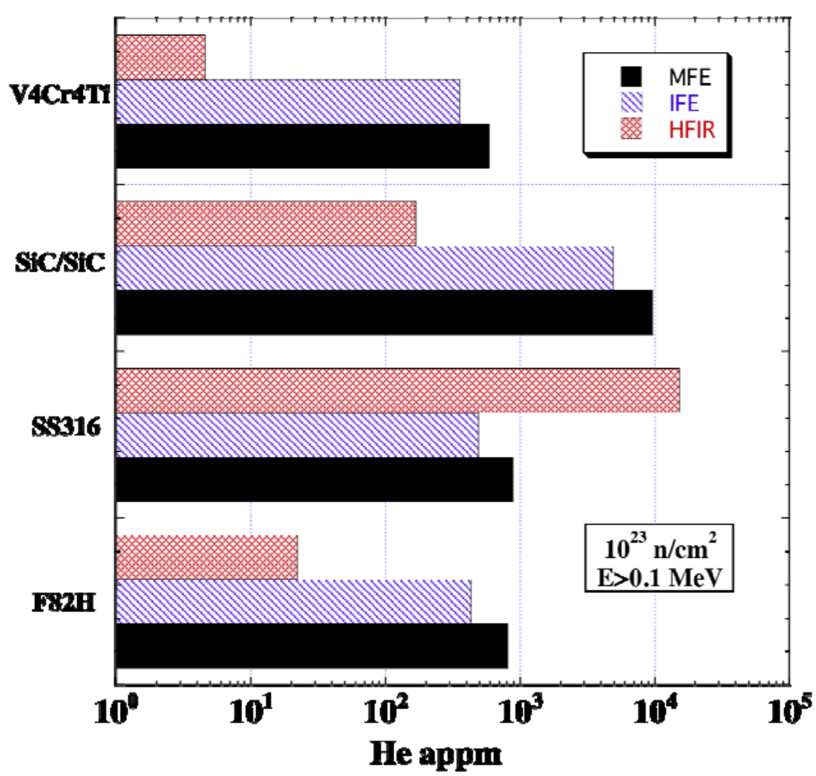

Figure 5. Structural material helium production comparison in fission and fusion environment.

The He/dpa and H/dpa ratios are given in Table IV for the candidate structural and plasma facing materials in MFE and IFE systems as well as in HFIR. The results are compared in Figs. 6 and 7 for the candidate structural materials. It is clear that the He/dpa ratio in a fission reactor is significantly lower by up to two orders of magnitude depending on the material. The only exceptions are for SS316 due to the enhanced helium production in B and Ni and for Be which has a low energy threshold for reactions producing helium. The H/dpa ratio is also lower following fission reactor irradiation with the reduction dependent on the material irradiated. The effect of the softer spectrum in fission reactors on H/dpa ratio is not as pronounced as that on He/dpa ratio due to the relatively lower threshold energies for reactions producing hydrogen than for reactions producing helium. The results provide guidance to simulate the fusion environment in fission reactor irradiation experiments by possible helium or hydrogen ion implantation.

TABLE IV. GAS PRODUCTION PER DPA IN FUSION SYSTEMS AND HFIR

Material	He appm per dpa			H appm per dpa		
	MFE	IFE	HFIR	MFE	IFE	HFIR
F82H	9.7	6.6	0.31	43	29	4.9
SS316	10.1	7.1	202	54	38	24
SiC/SiC	87	48	1.53	32	18	1.93
V4Cr4Ti	4.1	3.0	0.05	21	16	0.58
Be	410	249	333	6.3	3	0.008
W	0.6	0.5	0.0008	1.8	1.2	0.003
C	195	98	1.8	0.04	0.07	0.0003

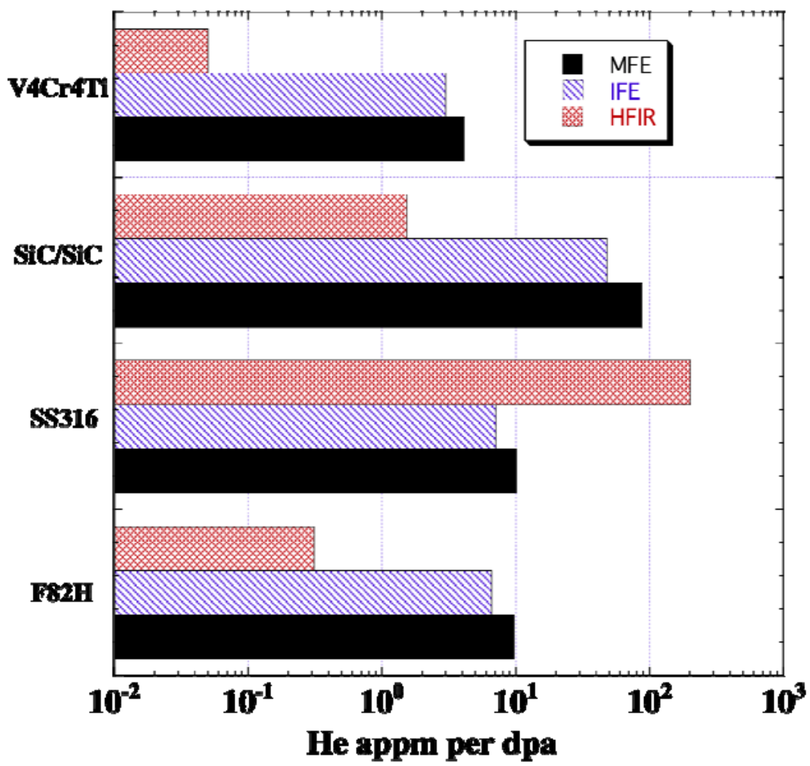

Figure 6. Structural material He/dpa ratio comparison in fission and fusion environment.

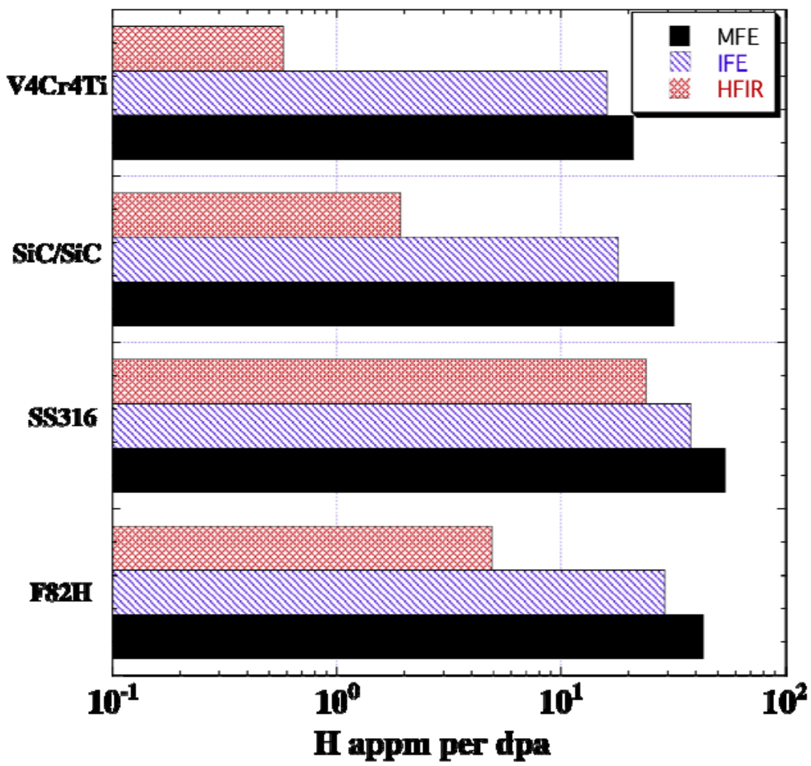

Figure 7. Structural material H/dpa ratio comparison in fission and fusion environment.

V. Summary and Conclusions

Irradiation tests for candidate fusion structural and plasma facing materials are usually performed in fission reactors such as HFIR at ORNL. To understand how to correlate and extrapolate results from such tests to the actual environment in fusion systems, we performed calculations to quantify the damage parameters in the leading structural and plasma-facing armor material candidates when used in MFE and IFE systems and when irradiated in HFIR. The structural materials considered are the ferritic steel alloy F82H, austenitic steel SS316, the vanadium alloy V4Cr4Ti and the SiC/SiC composite. Plasma-facing armor material candidates included Be, W, and CFC. Atomic displacement damage and gas production rates are greatly influenced by the neutron energy spectrum. The results indicate that for the same neutron wall loading, atomic displacement damage is slightly lower in IFE systems than in MFE systems but gas production is about a factor of 2 lower due to the softened neutron spectrum. In addition, much lower gas production is obtained in samples irradiated in fission reactors. For the same atomic displacement damage level, gas production is significantly lower in fission irradiation compared to that in the first wall of a fusion blanket with the effect strongly dependent on the material. For SS316, the high helium production in B and Ni by low energy neutrons yields higher helium production following irradiation in fission reactors. The results of this work will help guide irradiation experiments in fission reactors to properly simulate the damage environment in fusion systems by possible gas implantation and will facilitate extrapolating to the expected material performance in fusion systems. In addition, the results represent a necessary input for modeling activities aimed at understanding the expected effects on mechanical and physical properties.

Acknowledgment

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