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D-³He and D-T Reactors with Impact
on Reactor Availability**

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May 1994

UWFDM-951

Prepared for the Eleventh Topical Meeting on the Technology of Fusion Energy,
June 19–23, 1994, New Orleans LA

FUSION TECHNOLOGY INSTITUTE

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ASSESSMENT OF FIRST WALL LIFETIME IN D-³He AND D-T REACTORS WITH IMPACT ON REACTOR AVAILABILITY

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ABSTRACT

The neutron yield in a D-³He reactor is much lower than that in a D-T reactor of equivalent power. Therefore, the rate of neutron damage and gas production in the first wall of D-³He reactors is lower by more than an order of magnitude. Whereas different structural materials proposed for use in commercial fusion reactors will last the reactor lifetime of 30 full power years in a D-³He reactor, frequent replacement of the first wall and blanket will be required during the lifetime of a D-T power reactor. The blanket modules may require 30 replacements depending on the material used and the maximum allowable damage level. The down time required for replacement of the first wall and blanket in a D-T reactor will impact the reactor availability and consequently the cost of electricity. It appears that a D-³He reactor should have a 10% advantage in availability over a D-T reactor.

I. INTRODUCTION

In a tokamak fusion power reactor utilizing the D-³He fuel cycle, only a small fraction of the fusion power (~5%) is carried by neutrons. About 65% of these neutrons are 2.45 MeV produced from DD reactions and the rest are 14.1 MeV DT neutrons. In comparison DT fusion reactors have 80% of the fusion power carried by 14.1 MeV neutrons. Hence, the neutron wall loading at the first wall (FW) of a D-³He reactor is much lower than that in a D-T reactor of equivalent power. On the other hand, the peak surface heat flux in the FW of a D-³He reactor is relatively high (~2 MW/m²). This places a premium on the design of the FW which should be capable of removing the high surface heat without exceeding temperature and stress limits. As a result of the lower

neutron wall loading, the rate of neutron damage and gas production in the FW of D-³He reactors is lower than that in a D-T reactor by more than an order of magnitude. The FW lifetime is determined primarily by neutron damage and gas production rates. In this paper, peak damage and gas production rates are determined for different structural materials exposed to the nuclear environment of both D-T and D-³He commercial power reactors.^{1,2,3} The structural materials considered include austenitic steel 316 SS, ferritic steel HT-9, vanadium alloy V5Cr5Ti and SiC composite. The need for FW and blanket replacement during the commercial reactor lifetime of about 30 full power years (FPY) will be assessed. The down time required for replacement of the FW and blanket in a D-T reactor will impact the reactor availability and consequently the cost of electricity. An attempt to quantify the impact on availability will be made for reactors using the four structural materials.

II. CALCULATIONAL PROCEDURE

Neutronics calculations have been performed to determine the peak damage and gas production rates in the FW of fusion power reactors utilizing the D-T and D-³He fuel cycles. The one-dimensional discrete ordinates code ONEDANT was used with nuclear data based on the ENDF/B-V evaluation. The model used for D-T reactors included a FW made of a 4-mm-thick coolant layer sandwiched between two 3-mm-thick structural plates. The FW is backed by a 50-cm-thick blanket zone. The blanket composition affects neutron reflection and, hence, impacts the damage parameters in the FW. Different blanket concepts are used for the four structural materials considered. For 316 SS, a Li₂O/Be/H₂O/SS blanket concept is used. For HT-9 structure, a self-cooled

LiPb blanket is considered. A self-cooled Li/V blanket is used for the case with V5Cr5Ti FW and for the case where SiC structure is used, a Li₂O/Be/He/SiC blanket concept is used. In D-³He reactors a high synchrotron radiation power is produced and a reflective FW coating is needed to reflect most of this energy back into the plasma. The model used in this analysis utilizes a 1.5-mm-thick Be coating. The FW configuration is similar to that used in the model for D-T reactors. Since tritium breeding is not needed in D-³He reactors, the blanket used behind the FW in the model for D-T reactors is replaced by a shield made of the FW structural material with 20% coolant. Helium gas is used as coolant in the SiC case and water is utilized in the other cases.

The toroidal effect and neutron source profile in a tokamak result in a peaked neutron wall loading occurring in the outboard region at midplane. To first order, the FW damage scales with the neutron wall loading. Commercial D-T fusion reactors are expected to have average and peak neutron wall loadings around 3 and 5 MW/m², respectively.¹ The neutronics results obtained for D-T reactors are scaled to a neutron wall loading of 5 MW/m² to determine the expected peak FW damage and gas production rates. The fraction of fusion power carried by neutrons in a D-³He reactor depends on temperature and D-³He mix ratio. The average and peak neutron wall loadings in commercial D-³He fusion reactors, with equivalent net electric power, are expected to be around 0.1 and 0.15 MW/m², respectively.^{2,3} About 75% of the neutron power is carried by 14.1 MeV DT neutrons with the rest being carried by 2.45 MeV DD neutrons. The energy spectrum of the neutron source used in the calculations reflects this mix of DT and DD neutrons. The results are normalized to a neutron wall loading of 0.15 MW/m² to determine the expected peak FW damage and gas production rates.

The impact of blanket replacement on fusion reactor availability is very design dependent and extremely complex. Since there are no fusion reactors on which we can base the experience, we must rely on data available from fission reactors and make a qualitative assessment to determine the penalty of blanket replacement on availability. A 1976 study by McDonnell-Douglas⁴ was the first to signal that blanket replacements in fusion reactors will be very difficult and time consuming. For example, they estimated the time to replace a single blanket sector in UWMAK-I⁵ at 115 days, UWMAK-III⁶ at 48 days and the Culham MARK II⁷ reactor at 35 days. A more recent study at AEA Fusion (Culham

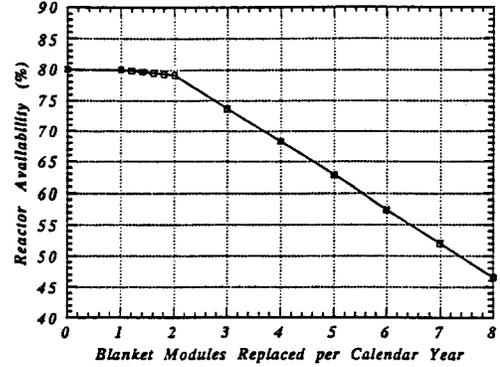


Fig. 1. Reactor availability as a function of number of blanket modules replaced per year.

Laboratory)⁸ estimated the replacement time for 16 blanket sectors in a single null fusion reactor design of the ITER type. The lifetime of the divertor plates was 2 calendar years. The reactor unavailability due to blanket replacement was 20% and that of divertor plate replacement was 9%. Since some of the work for both is done in parallel, the overall impact on availability was 25%. The conventional and auxiliary plant unavailability of 13% also goes in parallel with the 25% and thus is not additive. However, the unplanned unavailability of 7% is additive and brings the total to 32%, resulting in an overall availability of 68%. The irreducible unavailability, even with no blanket replacement, is 20% which is made up of auxiliary plant maintenance of 13% with parallel divertor replacement and the unplanned unavailability of 7%.

Planned unavailability of 25% for replacing four blanket sectors and one half of the divertor plates per year is 91 days. Of these, 12 days are for pre- and post-replacement preparation, which is the same regardless of how many sectors are replaced. From this we obtain the time needed for replacement of a single blanket sector at 19.75 days. Figure 1 shows the overall reactor availability as a function of the number of blanket sectors replaced per calendar year. It is assumed that the replacement frequency for the divertor is proportional to that of the blanket. Note that replacement of a single blanket sector per year draws no penalty, since the time needed to accomplish this (~9%) is within the 13% allocated for auxiliary plant maintenance. The impact is minimal at 2 sectors (79.1%) and decreases linearly to 46% for 8 sector replacements per year. Note that the 4 replacements gives the 68% availability arrived at by the study.⁸ This methodology will be used to determine the impact on reactor availability.

TABLE I

Peak Damage and Gas Production Rates
for the Different Structural Materials

	dpa/FPY		He appm/FPY	
	D-T	D- ³ He	D-T	D- ³ He
316 SS	51	2.20	882	19.6
HT-9	90	2.16	750	16.6
V5Cr5Ti	51	2.36	320	7.1
SiC	49	3.45	7070	149.1

III. FIRST WALL LIFETIME

The useful lifetime of the structural material in a fusion reactor is determined by the requirement that its structural integrity be preserved. For metallic materials, the key indicators are swelling and embrittlement. The main concerns for SiC are the effects of irradiation on dimensional changes and fracture toughness as well as the burnup of the SiC molecules. The two parameters that have the most impact on the lifetime indicators are the dpa level and amount of helium generated.

The peak dpa and helium production rates have been determined for the four structural materials when used in power reactors utilizing the D-T or the D-³He fuel cycles. The results are given in Table I. The relatively high dpa rate for HT-9 in the D-T reactor is attributed to the neutron multiplication and reflection from the lead in the LiPb. The very large helium production rate in SiC results from the (n,3 α) reactions in C. It is clear that D-³He fuel results in significantly lower damage and gas production rates. Larger reduction is obtained in the gas production rates which result from high energy threshold reactions. This is demonstrated by comparing the contributions from the high energy DT neutron components to the damage and gas production rates in the D-³He reactor as shown in Figure 2. While the DT neutrons represent only 35% of the source neutrons, they are responsible for almost all of the gas production. The contribution of DT source neutrons to the dpa rate is less than their contribution to the neutron wall loading (75%). This is due to the larger number of low energy DD neutrons that can still produce atomic displacements. The helium to dpa ratio is given in Figure 3 for the candidate structural materials in D-T and D-³He reactors. The ratio is lower in D-³He reactors due to the softer neutron energy spectrum.

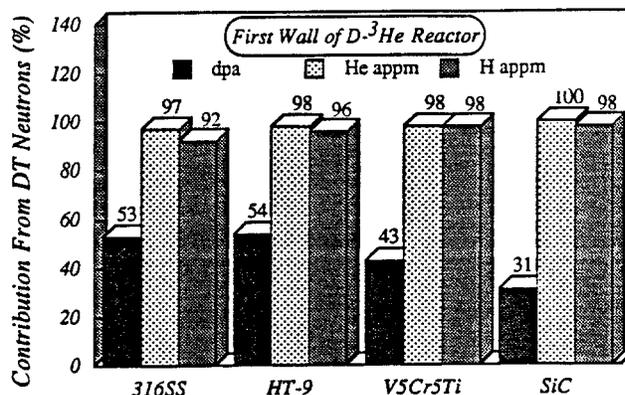


Fig. 2. D-T neutron contribution to the damage and gas production rates.

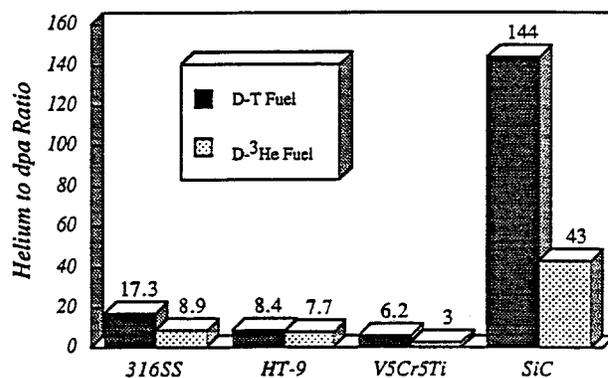


Fig. 3. He/dpa ratio for D-T and D-³He reactors.

Unfortunately, there is relatively little information on effects of neutron irradiation on the structural materials in commercial fusion reactors. Hence, no well defined damage parameter limits are available. For this reason, the expected lifetimes for the candidate structural materials are given in Figure 4 as a function of the dpa limit. Even at the lower dpa limit of 100 dpa, all structural materials are expected to survive the whole D-³He reactor lifetime of 30 FPY. On the other hand, frequent FW and blanket change-outs will be required in a D-T reactor. Each blanket module has to be replaced about 15 times over the reactor lifetime if the dpa limit is 100 dpa with 12 more replacements needed for a self-cooled LiPb/HT-9 blanket. For SiC, the parameter that limits the useful lifetime is expected to be the burnup of SiC molecules. The burnup rate is determined for SiC in both D-T and D-³He reactors. The expected FW lifetime is given in Figure 5 as a function of maximum allowed burnup fraction. It is clear that significant enhancement of SiC lifetime is achieved in a D-³He

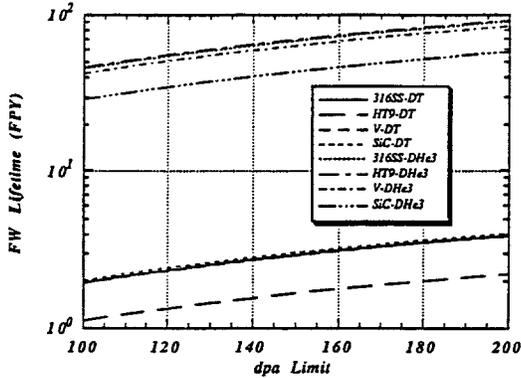


Fig. 4. Expected FW lifetime of candidate structural materials as a function of dpa limit.

reactor. Even for the low burnup limit of 1%, SiC first walls are lifetime components in D-³He reactors. Several replacements will be required in D-T reactors with the frequency depending on the burnup limit.

IV. IMPACT ON REACTOR AVAILABILITY

Because the dpa limit for these materials is still not well known, the availability is determined as a function of dpa limit from 100 to 200. Figure 6 shows the availability as a function of dpa limit for the four reactor designs. The common assumption in this exercise is that the reactors have 20 blanket sectors and all have the same level of difficulty for replacement. Figure 6 demonstrates the effect of structural/breeder/coolant material on the dpa and directly on availability. The reactors utilizing SiC, 316 SS and V are bunched together, ranging in availability from 58-71%, while the ferritic steel (FS) reactor is somewhat lower at 45% to 60%. This appears to penalize FS, but as a matter of fact is due to neutron multiplication in the LiPb. Figure 7 shows the availability of a SiC structure/He cooling/solid breeder and a generic metallic structure in a Li self-cooled configuration. The SiC is better than the metallic structure by only one percentage point along the whole curve. At 200 dpa limit, the SiC blanket achieves an availability of 71%, whereas the ARIES I reactor design assumed 76%.

In Figure 8, the reactor availability is shown as a function of the SiC burnup fraction from 0 to 10%. For a fractional burnup of 5% the availability is 71%. It is ludicrous to imagine that any material could maintain reasonable structural integrity with 5% of its atoms destroyed. A more likely value would be 2-3% making the availability in the range of 54%-63%.

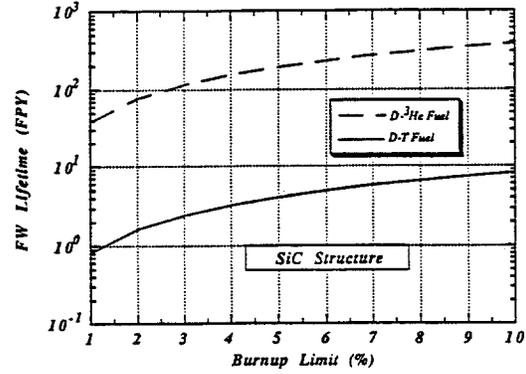


Fig. 5. SiC lifetime as a function of burnup.

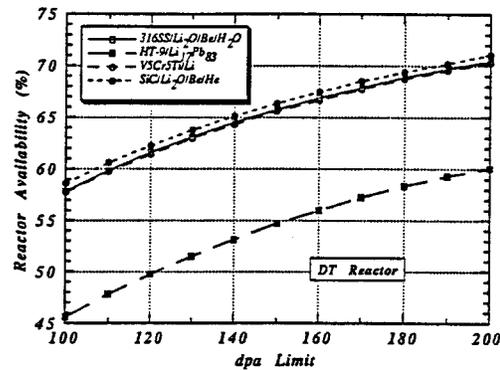


Fig. 6. Availability vs. dpa limit for D-T reactor.

Here the value of D-³He becomes obvious. Figure 4 shows that even at a dpa limit of 100, all the reactor designs achieve a lifetime of 30 FPY, which is 37.5 calendar years at 80% availability. Statements have been made that disruptions in the higher current carrying D-³He reactors will have serious consequences. However, since no tritium breeding is needed in a D-³He reactor, the FW and shield could be made to be capable of withstanding very high electro-mechanical forces. Furthermore, recent Russian experiments⁹ have shown that vapor shielding has an effect of more than an order of magnitude higher than had been originally assumed. In situ recoating with Be of FW elements can also be envisaged.

Finally, it can be seen from Fig. 1 that up to two blanket sectors can be replaced per calendar year while maintaining a 79-80% availability. From this we can infer that a D-³He reactor can achieve an availability on the order of 80% even if all the divertor plates are replaced every two years and up to two shield sectors are replaced per year. It is important that this fact be recognized and factored into the cost of electricity.

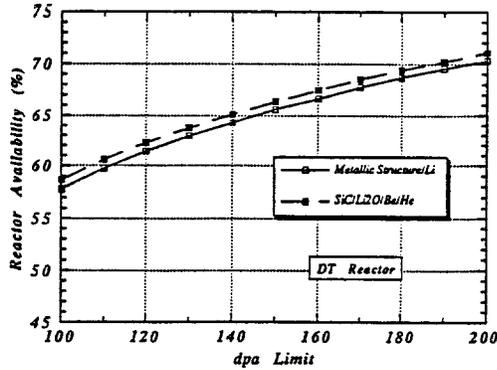


Fig. 7. Availability of a SiC structure and a generic metallic structure in a Li self-cooled design as a function of dpa limit.

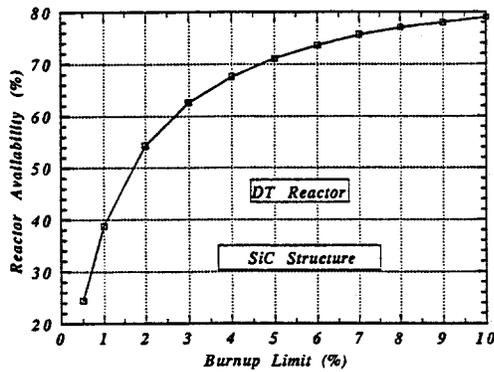


Fig. 8. Availability as a function of SiC burnup limit.

V. CONCLUSIONS

The reduced neutron yield and softer neutron energy spectrum results in neutron wall loadings at the FW of a D-³He reactor much lower than in a D-T reactor of equivalent power. Thus, the rate of neutron damage and gas production in a D-³He reactor FW is lower than in a D-T reactor by more than an order of magnitude. Damage and gas production calculations for the different candidate materials proposed for fusion reactors predict that the FW and shield in a D-³He reactor will last the whole reactor lifetime of 30 FPY. On the other hand, up to 30 replacements of the FW and blanket may be required for a D-T power reactor depending on the structural material used and the maximum allowable damage level. This is a major advantage for a D-³He reactor. Qualitatively, it appears that a D-³He reactor under pessimistic assumptions should have a 10% advantage in availability over a D-T reactor using the most optimistic assumptions.

An irreducible value of 20% unavailability is needed due to balance of plant maintenance and unscheduled outages. This implies an availability of 80% for D-³He reactors and 70% for D-T reactors. A 3% fractional burnup limit in a SiC material dictates an availability of only 63%.

ACKNOWLEDGEMENT

This work was supported by the Wisconsin Electric Utilities Research Foundation, the Grainger Corporation and Fusion Power Associates

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