First Wall Surface Problems for a D-T Tokamak Reactor

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January 1974

UWFDM-80

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Abstract

The effects of deuterium, tritium, helium and neutron bombardment on surface degradation of the first wall of a 5000 MW_{th} D-T reactor has been analized. The effects of both sputtering and blistering have been analized and applied to 316 stainless steel operating at temperatures from 300 to 500°C. It has been calculated that the total wall erosion rate is 0.22 mm/year and that 14 MeV neutron sputtering accounts for two thirds of this number. Sputtering from all neutrons results in ~0.17 mm/year erosion. The calculated erosion rate is 2-3 times that which would be allowable for a 30 year first wall lifetime.

Introduction

The first wall of a D-T fusion reactor will be subject to intense photon, charged particle and neutron bombardment while operating at high temperatures. The particle bombardment can cause considerable wall erosion due to the sputtering of atoms off of the surface of the wall. Furthermore, if the incident particles are gas atoms which come to rest in the material, there can also be substantial blistering, flaking and spallation of the wall surface.

The purpose of this paper is to investigate the practical significance of such wall erosion rates on the operation of a hypothetical 5000 MW_{th} power reactor. It must be cautioned that the conclusions of this work apply only to the speçific reactor analyzed, UWMAK-I, which has been described in more detail elsewhere (1). The reader is cautioned about extrapolating these results to other systems.

Description of Reactor System

Some basic parameters of the UWMAK-I system are summarized in Table 1. The reactor is a Tokamak system utilizing a double null divertor which is described elsewhere in this conference (2). The efficiency of this divertor is assumed to be 90%. The power level is 5000 MW_{th} and the material of construction is 316 stainless steel. The neutron wall loading to the first wall is 1.25 MW/m^2 and the reactor is cooled with lithium.

A listing of the important plasma parameters for UWMAK-I are given in Table 2. Particular features to note are the ion and electron temperatures of 11 keV, average ion density of

TABLE 1

Basic Characteristics of UWMAK-I

Power	5000 MW_T (1500 MW_e)
Major Radius	13 m
Minor Radius	5 m
Divertor	Poloidal, Double-Null
Coolant	Lithium
Structural Material	316 SS
Neutron Wall Loading	1.25 MW/m^2
Magnetic Field	3.8 Tesla (on axis) 8.66 Tesla (max)
Magnets	Superconducting-Nb-Ti+Cu Cryogenically Stabilized
Power Cycle	Lithium-Steam

TABLE 2

Plasma Operating Parameters

Temperature	$T_i = T_e = 11$ kev
Density	$\bar{n}_i = 8 \times 10^{13} cm^{-3}$
Poloidal Beta	$\bar{\beta}_\theta = 1.08$
Stability Factor	$q(a) = 1.75$
Plasma Current	$I = 21 \times 10^6$ amps
Bremsstrahlung Enhancement Factor	7.5
Fractional Burnup	7.2%
Confinement Time	$\bar{\tau}_c = 14$ seconds
$\bar{\tau}_c/\tau$ neoclassical	1/1800
$\bar{\tau}_c/\tau$ Bohm	100

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$8 \times 10^{13} cm^{-3}$, a burnup of 7.2% and a confinement time of 14 seconds.

A schematic of one heat removal cell is shown in Figure 1. It is noted that the temperature of the first wall facing the plasma ranges from 300 to 500°C during operation. The stresses in the first wall due to the coolant pressure and the differential thermal expansion are shown in Figure 2 as a function of wall thickness. A surface wall loading of 22.6 watts/cm^2 and a nuclear heating rate of 13 watts per cm^3 were used to calculate the thermal stresses and a 300 psi coolant pressure was assumed. It is noted that the total stress in the wall is dominated by the coolant pressure below a thickness of ~1 mm and that is strongly influenced by thermal stresses above 3 mm.

The importance of Figure 2 with respect to surface problems can be better understood when the maximum operating stress (16,000 psi in the case of 500°C operation for 316 SS) is noted. The intersection of the maximum allowable stress with the calculated stress in the walls reveals that under UWMAK-I operating conditions, the first wall must not be less than 1 mm nor more than 4 mm thick. Another way of interpreting Figure 2 is that there is a maximum of 3 mm of 316 SS which could be eroded or corroded away during operation. Analysis of the Li corrosion on 316 SS at 500°C reveals a corrosion rate of 0.015 mm/year (3). If one would like the first wall to last for 30 years (a reasonable power plant lifetime) then the erosion rate due to sputtering and/or blistering cannot exceed ~0.085 mm/year.

Calculation of Particle Fluxes

The neutron flux and energy spectrum in the CTR blanket and in particular to the first wall have been calculated with the discrete ordinate program ANISN (4) using cross sections obtained from ENDF/B-III (5) as processed by MACK (6). The calculated fluxes are given in Table 3 and are given for two somewhat arbitrary energy ranges, greater than 10 MeV and between 0.1 to 10 MeV. The reason for this grouping will become apparent shortly.

The particle fluxes were obtained from particle and energy balance calculations on the plasma. To achieve a reasonable operating point, it was desirable to assume the particle confinement time could be made arbitrarily less than the neoclassical value. The confinement time chosen is three orders of magnitude less than the theoretical neoclassical value and 100 times longer than the Bohm value (Table 2). These calculations give the particle and energy flux at the edge of the plasma. The efficiency of the divertor in preventing these particles from getting to the wall in an unknown quantity. The experience with the Model C Stellarator divertor (7) and FM-1 divertor (8) plus some extrapolations for improvement led us to set the divertor efficiency at 90%. Thus the flux at the wall is 1/10 of the flux at the plasma edge.

The mean energy of the particles hitting the wall (23 keV) was obtained from the energy flux due to particle transport. It was arbitrarily assumed that the average energy of the

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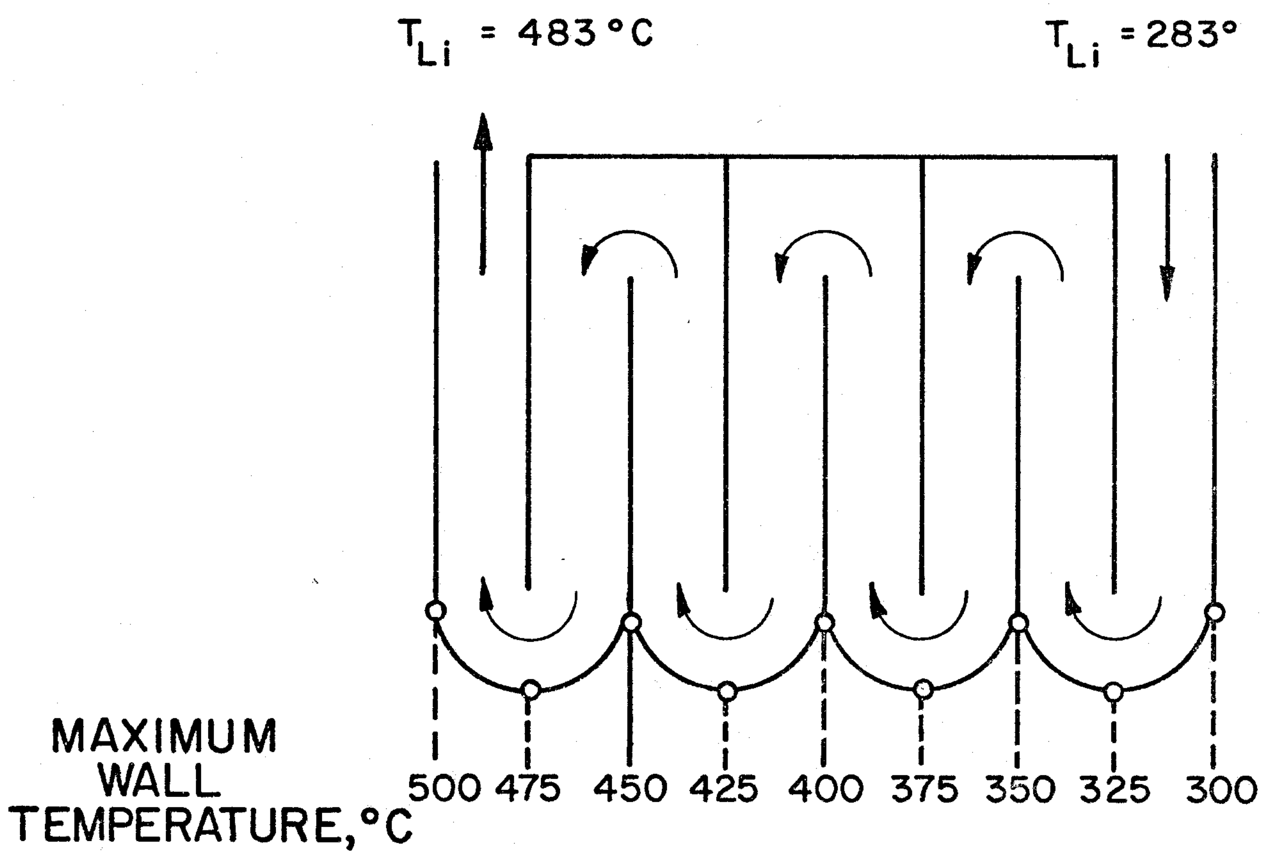

PLASMA

SPATIAL DISTRIBUTION OF TEMPERATURE IN UWMAK-I

Figure 1

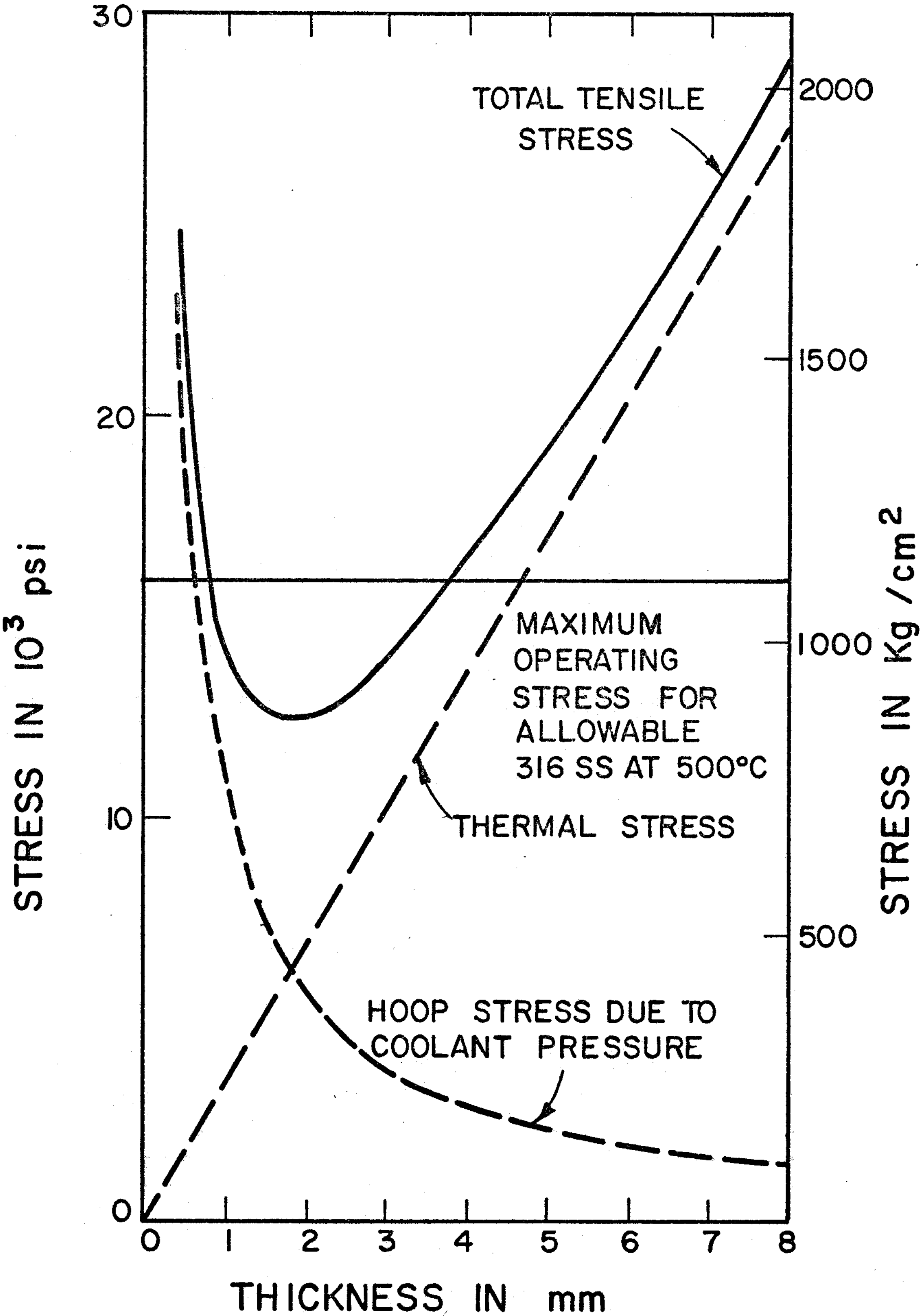

Figure 2 Stresses in a 316 SS Front Wall As a Function of Metal Thickness at 500°C and 300 PSIA Coolant Pressure

unthermalized helium ions was 100 keV. A theoretical analysis of the physical phenomena involved in the divertor is being undertaken to better determine the divertor efficiency, but experimental work is also clearly needed. The flux of metallic ions to the first wall was calculated as follows. All of the metallic ions sputtered from the first wall were assumed to re-enter the plasma region and thermalize with the plasma ions. It was then assumed that only 10% of the metallic ions escaping the plasma reach the first wall. The calculated fluxes and particle energies are given in Table 3

TABLE 3

Summary of Particle Fluxes to the First Wall of UWMAK-I

Ion	Mean Energy	Particle Flux $cm^{-2}sec^{-1}$
D+	23 keV	6.4×10^{13}
T+	23 keV	6.4×10^{13}
He+	23 keV	4.7×10^{12}
He+	100 keV	1.7×10^{11}
n	>10 MeV	9.4×10^{13}
n	0.1 to 10 MeV	3.4×10^{14}
Fe+	23 keV	2.5×10^{12}

Sputtering Coefficients

The number of atoms removed per incident particle, S, depends on many factors; the mass, energy and angle of incidence of the particle to name just a few (9). For the purposes of this study, we will assume that all the particles strike the first wall with normal incidence and we will rely, wherever possible, on experimental data for bombardment of Fe as a reasonable approximation for 316 stainless steel. The sputtering coefficients used for this are listed in Table 4.

The value of S for 23 keV deuterium and tritium ions on Fe was derived from experimental values for Cu (10), and scaling factors suggested by Pease (11). The values of 0.02 and 0.03 for D and T respectively on Fe should be considered valid to only within $\pm 50\%$.

The sputtering yield for helium ions will be estimated from data at lower energies and by comparison to a similar element (Cu) at higher energies (9). This analysis reveals a value of S = 0.15 for 23 keV helium on Fe and the value for 100 keV He is 0.03.

The estimates for neutron sputtering can be broken up into two terms; one for 14 MeV neutrons and the other for back scattered neutrons. Recent experiments by Kaminsky (12) with 14 MeV neutrons suggest that S = 0.2 for cold worked Nb at room temperature. Such a large S is found because of an unusual spike phenomena which causes large chunks of metal to be ejected. No explanation for such a large value has been given nor is it understood why it is almost two orders of magnitude from previous estimates. There are also indications (12) that this high value of S applies to other materials in addition to Nb so we will use the Kaminsky value until more detailed information is available for neutrons. We will arbitrarily assume that all neutrons of energy greater than 10 MeV cause the large value of S. Such an assumption is not critical because the neutron flux between 10-14 MeV is only ~10% of the uncollided 14.1 MeV flux and also allows those neutrons of $E<10$ MeV to be considered as fission neutrons.

The sputtering value for lower energy neutrons (0.1 to 10 MeV) has been suggested to be 5×10^{-3} atoms/ion (12) for Nb. If one uses Garber's(14) values of relative neutron sputtering rates, then a value of 9×10^{-3} atoms/neutron is predicted for iron. It must be remembered that neutron sputtering takes place on both sides of a wall, and proper care must be taken to include the value of two.

A self sputtering coefficient must now be chosen for iron. Based on data presented by Kaminsky (9), 45 keV Fe+ ions incident on iron have a sputtering yield of 3 atoms/ion. Although no data is presented for the change in the self sputtering coefficient with energy for iron on iron, data is available for copper on copper (9). Such a relationship was used to predict a self sputtering coefficient of 2.5 for 23 keV iron on iron.

Blistering

Irradiation of metal surfaces with energetic charges particles not only causes atoms to be sputtered from the first wall, but it can cause severe surface roughening and blistering. Qualitatively, the energetic ions (only hydrogen and helium isotopes will be considered here) displace atoms as they penetrate the solid. When they lose most of their energy, they slow down and become trapped because of their low diffusivity. Since the solubility of some of the gases in metals (e.g. helium) is extremely small, most of the gas precipitates into small bubbles. These small bubbles are formed near the end of the range for the gas atom and this region also corresponds with that for maximum vacancy production. The bubbles can capture these vacancies, grow and eventually coalesce with other bubbles to form lenticular bubbles below the surface of the metal. If enough atoms are injected at an elevated temperature, the pressure in these bubbles will be high enough to deform the metal surface causing it to protrude above the original surface. Eventually, this "blister" can rupture causing a large flake of the wall material to be spalled off.

Blister formation has been found with helium ions in Nb (15-24), Mo (22,25,26), W (27), Pd (28), Cu (29), V alloys (18,22,24) and stainless steel (28,30,32). There have also been some instances where blisters have been formed by deuteron irradiation of Nb (24,33), Mo (27), Be (27), and stainless steel (27). No attempt will be made here to review the literature and the reader is referred to articles listed above for a more extensive bibliography.

At the present time, the size, density, and shape, and critical fluence for the formation of blisters is known to be a function of at least nine parameters:

1. Energy of ions (i.e. their range) (17,19)
2. Diffusivity of injected ions (20)
3. Solubility of gas atoms in matrix (20)
4. Yield strength of the metal (25)
5. Temperature of the metal during bombardment (16-19, 22,32)
6. The dose rate of bombarding ions (24)
7. Total dose (15, 17-19)
8. The orientation of the crystal structure to the ion beam (16-20)
9. The metallurgical state of the sample prior to irradiation, i.e., cold worked vs annealed (15,18)

The occurrence of this phenomenon is so recent that no comprehensive theory has been developed to adequately predict the extent of wall erosion due to blistering. In the absence of such a theory, we will only be able to estimate the erosion rates based on simple concepts.

There have been three recent studies which have dealt with blistering in austenitic stainless steel.

Bauer and Thomas (31) have studied the temperature dependence of helium re-emission from 316 SS after 300 keV bombardment. The samples were implanted at a flux of 6.25×10^{13} $cm^{-2} sec^{-1}$. It was found that fractured helium blisters could be observed on the steel surface concident with the sudden and dramatic release of helium. The critical fluence for blister formation was $\sim 1.4 \times 10^{18} cm^{-2}$ at -170°C, $1 \times 10^{18} cm^{-2}$ at 300°C, $7 \times 10^{17} cm^{-2}$ at 500°C and $\sim 4 \times 10^{17}$ at 700°C.

Verbeek and Eckstein (26) injected H+, D+ and He+ into 4301 stainless steel at 15 and 150 keV. Blisters were formed in steel at both ion energies and it was found that the critical fluence for the occurrence of blisters at 300°K was $1.2\text{-}4 \times 10^{17} cm^{-2}$ for 15 keV helium bombardment. Blisters are even formed by 15 keV D+ ions at 27 and 347°C. The critical fluence for deuterium blister formation was $\sim 5 \times 10^{18} cm^{-2}$ and the blisters appeared to be closely associated with grain boundaries and precipitates. It was concluded that hydrogen isotope blisters do not significantly contribute to wall erosion even though they may cause localized pitting.

Das and Kaminsky (30) have investigated the blister formation in 304 SS between room temperature and 550°C. (five hundred keV helium ions were used) It was concluded that the maximum temperature for blister exfoliation occurs at ~500°C and that the effective value of S (hereafter referred to as S') at that temperature is 0.48. This value drops to 0.22 at room temperature. Both of these values are consistent with previous work which yield S' ≅ 0.1 For V at RT and 600°C, and S' = 0.2 for Nb at RT. More recent work by Kaminsky (12) has yielded S' values of 3 for 100 keV ions on 304 SS. It appears that the lower energies are more effective in removing the surface layers in steel.

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A crude method to estimate the maximum wall erosion rate is to assume that when the critical fluence is reached, an entire layer of the metal equal in thickness to the range of the incoming particle will be exfoliated. (Note: This is a rather conservative approach as experience shows that not all the surface comes off at one time). The effective wall erosion rate for 316 SS can be calculated by

$$S' = \frac{R}{(\phi t)_c} \times \frac{N_o \rho}{A_w} \cong \frac{R}{(\phi t)_c} \, (8.7 \times 10^{22})$$

where

$(\phi t)_c$ is the critical fluence for exfoliation

R is the range of the ion

N_o is Avogadro's Number

ρ is the density

A_w is the atomic weight

For 300 keV helium, $R \cong 0.98$ microns, $(\phi t)_c \sim 10^{18}\ cm^{-2}$ and the value of $S' \cong 8$. Such a number is an order of magnitude above Das and Kaminsky's 500 keV value (30) but less than a factor of 3 larger than the 100 keV data. This high value of S' indicates the large degree of conservatism built into this simple model. Some of the helium may get to the surface without forming major blisters while other helium certainly "leaks" out from the subsurface when a blister bursts.

The calculations of wall erosion in UWMAK-I will include a value of $S' \cong 3$ for 100 keV helium consistent with the Das and Kaminsky value for 100 keV particles. We will assume that 23 keV helium blistering occurs with $S' \cong 1$ due to the shorter ranges. However, the latter assumption may underestimate the wall erosion rates and future data should be closely examined.

It is very difficult at this time to assess wall erosion due to D+ and T+ bombardment. Verbeek and Eskstein (20) have shown that the threshold fluence is a factor of 10 higher for the hydrogen isotopes compared to helium and that the blister formation is very inhomogeneous. We will take a very conservative approach at this time for hydrogen blistering and assume that the effective wall erosion rate is ~1/100 that of equivalent energy helium ions, yielding a value of $S' \cong 0.01$.

Erosion Rates in UWMAK-I

A summary of the individual as well as total erosion rates is given in Table 4, and the results are displayed as a function of time in Figure 3. There are several points worth noting. First of all, the use of a 90% divertor results in a wall erosion rate of ~0.22 mm/year or 6.6 mm in 30 years of operation.

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TABLE 4

Summary of First Wall Erosion Rates in UWMAK-I

Ion	Mean Energy-keV	S	Flux $cm^{-2}sec^{-1}$	Erosion Rates mm/year	% Total[a)]
			Sputtering		
D+	23	0.02	6.4×10^{13}	0.0047	2
T+	23	0.03	6.4×10^{13}	0.0070	3
He	23	0.15	4.7×10^{12}	0.0026	1
He	~100	0.03	1.7×10^{11}	0.00002	-
n	>10,000	0.2	9.4×10^{13}	0.14[b)]	64
n	0.1-10,000	0.009	3.4×10^{14}	0.022[b)]	10
Metal	23	2.5	2.6×10^{12}	0.023	10
		Total Sputtering		~0.20	
			Blistering		
He	23	1	4.7×10^{12}	0.017	8
He	~100	3	1.7×10^{11}	0.0019	1
D+	23	0.01	6.4×10^{13}	0.0023	1
T+	23	0.01	6.4×10^{13}	0.0023	1
		Total Blistering		~0.024	

Total Wall Erosion Rate ~0.22 mm/year

a) will not total 100% due to round off

b) includes both sides of wall

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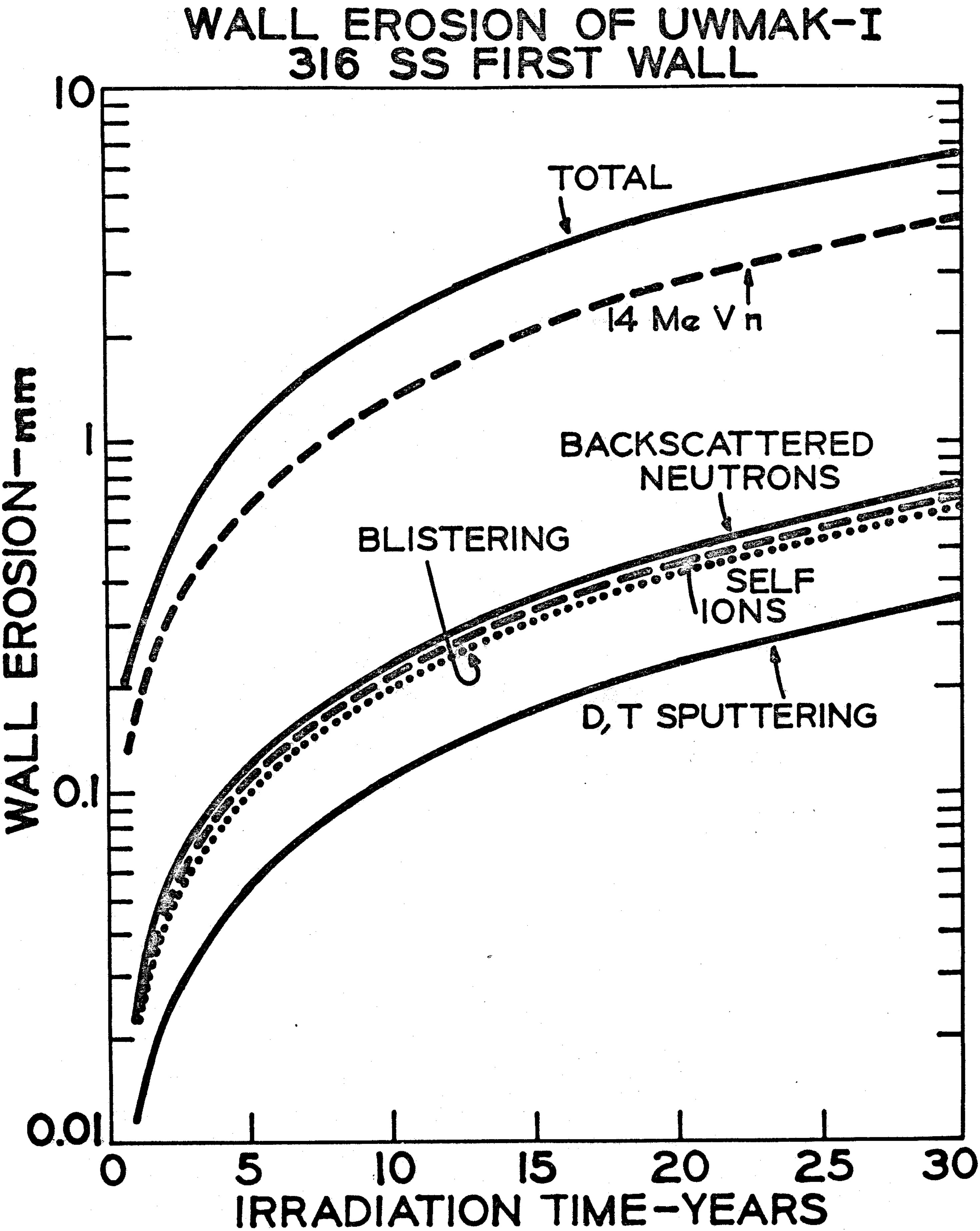
WALL EROSION OF UWMAK-I
316 SS FIRST WALL
10
1
0.1
0.01
WALL EROSION-mm
TOTAL
14 MeV n
BACKSCATTERED
NEUTRONS
BLISTERING
SELF
IONS
D, T SPUTTERING
0
5
10
15
20
25
30
IRRADIATION TIME-YEARS

Figure 3

Secondly, almost two-thirds of the wall erosion comes from the high energy neutrons and about three quarters comes from the total neutron flux. The rest of the wall thinning is equally divided between sputtering and blistering.

Finally, the effect of no divertor al all on the wall erosion rate would be to raise the thinning rate by a factor of ~3.5 instead of 10 which might be indicated by the efficiency. This observation stems from the high dependence of erosion on neutron sputtering and the assumption of a lack of any cascading effects of the self ion bombardment.

The physical significance of the first wall erosion rates calculated for UWMAK-I is that they are more than a factor of 3 higher than necessary for the first wall to last for the projected lifetime of the plant (30 years). In fact, it is calculated that the allowable 3 mm of wall erosion will be used up in only 13 years of operation at UWMAK conditions! Clearly, methods must be devised to reduce the surface degradation, but increasing the divertor efficiency does not appear to be the entire solution. The erosion of the first wall with 100% efficient divertor operation would still be ~0.16 mm/year (due to neutron sputtering) or roughly twice that allowable for 30 years of operation. Therefore, methods of reducing the 14 MeV neutron sputtering must be devised. The present state of the experimental data and theoretical analysis must be greatly expanded in that area.

Finally, we would be remiss if we did not point out that there are other forms of radiation damage in a D-T reactor which are even more restrictive than the surface erosion(33). Irradiation embrittlement and swelling will limit the life in UWMAK-I to 2 and 6 years respectively. Obviously, these damage mechanisms must be understood and circumvented before the surface damage problems become restrictive. A concerted effort in all three areas of radiation damage; embrittlement, swelling and surface effects is required if we wish to build safe and economical fusion reactors.

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