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By

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Surface Effects in Controlled Thermonuclear Fusion*

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ABSTRACT

During the operation of large size plasma facilities and future controlled thermonuclear fusion reactor, the surfaces of such major components as container walls, beam limiters, diverter walls and beam-dump walls of the injector region will be exposed to particle and photon bombardment from primary plasma radiations and from secondary radiations. Such radiations can cause, for example, physical and chemical sputtering, blistering, particle- and photon-impact induced desorption, secondary electron and x-ray emission, backscattering, nuclear reactions, photo-decomposition of surface compounds, photocatalysis, and vaporization. Such effects in turn can (a) seriously damage and erode the bombarded surface and (b) release major quantities of impurities which will contaminate the plasma.

For a determination of the plasma impurity concentrations and the surface erosion rates it is necessary to know the yield values of the various particle emission phenomena. At this time our knowledge of such yield values is only fragmentary for the plasma parameters and the materials envisioned for CTR applications. To what extent the yield values will be affected by synergistic effects due to the simultaneous bombardment of surfaces by high-fluxes of energetic particles of various types and photons is almost completely unknown. The effects of some of the major surface phenomena on the operation of plasma facilities and future fusion reactors will be discussed.

INTRODUCTION

The U. S. fusion power development program is aimed at the first significant production of fusion power on an experimental scale in the early 1980's, and a demonstration of the commercial production of fusion power in 1995-1997, according to a status report by Robert L. Hirsch.¹ In order to achieve this goal, four major concepts are being pursued in the U. S. at this time. Three concepts use magnetic fields to confine a plasma for either pulsed or steady state operation: the tokamak, theta-pinch, and mirror devices. The fourth concept is laser-fusion, which utilizes inertia to hold a plasma for a very short period of time ($\sim 10^{-9}$ sec.).

In order to determine on what time scale what kind of surface science data will be needed to help in the fusion power effort, it is necessary to review briefly the DCTR program plan.¹ The development of power reactors calls for a fusion test reactor (FTR) to begin operation in 1980, a first experimental power reactor (EPR) to begin operation in the mid 1980's, and a demonstration power reactor (DPR) to begin operation in 1995-2000. The need for surface science data arises already during the design stages of such reactors. Fig. 1 shows a time chart which gives approximate dates for surface science data needed for the development of various reactor systems. Since, for example, the design of the FTR will begin in FY 1976 and be completed in FY 1977, the urgency for having the required surface science data available for the design becomes apparent. The time chart also indicates the approximate dates at which surface science data will be needed for materials and components development and systems construction, as well as for improvements of the operation of the various reactors. The approximate dates for a fusion engineering research facility (FERF) have been included, a device which will

be valuable for materials research and especially for surface radiation studies. Also included is the construction and operation of a second experimental power reactor (EPR II). Additional surface science data will be needed during the next five years for the design, and/or construction, and/or operation of plasma devices such as the tokamak systems PLP, PPX, HFO, ISX, and Doublet III, or the theta-pinch systems Scyllac, staged theta-pinch experiment, and staged torus, or the mirror systems LBLT, 2XII, LITF, and MXI. These machines will also generate valuable information about plasma-surface interactions which will be of use for the design and construction of the systems listed in Figure 1.

For a determination of the amount of atoms released from surfaces and of the surface erosion rates caused by plasma radiations it is necessary to know both the yield values of the various particle emission phenomena and the fluxes of the various types of projectiles (atoms, ions, electrons, neutrons, photons) striking the surfaces of exposed components. At this time our knowledge of such yield values and erosion rates is only fragmentary for the plasma parameters and the materials envisioned in CTR applications. To what extent the yield values and the erosion rates will be affected by synergistic effects due to the simultaneous bombardment of surfaces by high-fluxes of energetic particles of various types and photons is almost completely unknown. [For recent reviews see references 2-5.] However, only with the proper identification and understanding of the most deleterious effects will it become meaningful to develop methods to reduce and possibly eliminate serious plasma contamination and wall erosion.

In the following a review of the types of plasma radiations expected in large size plasma devices and future controlled thermonuclear fusion reactors will be given. In addition, potential sources

for plasma contamination and possible methods to reduce plasma contamination will be discussed. A summary of some of the major surface erosion phenomena and of solutions to reduce such effects will be included. The material presented here summarizes some of the main conclusions of recent articles published by various authors [see references 2-3].

Plasma Radiations

For an estimate of the number of gaseous impurities released from surfaces and of the surface erosion rates it is necessary to know the flux ϕ_μ (number of projectiles $\text{cm}^{-2}\text{sec}^{-1}$) of a particular projectile species μ (e.g. D^0 , T^0 , He^0 , He^+ , neutron, electron, photon) for given mean energies $\bar{E}$ (or given energy spectrum) and average angles of incidence $\bar{\alpha}$ (or a range of angles). The flux values for particles and photons leaving the plasma and striking exposed component surfaces depend not only on the particular type of plasma device or fusion reactor (e.g. tokamak reactor, mirror reactor, theta pinch reactor), but also on its design parameters and its operating conditions. For example, Table 1 illustrates the significant differences in the estimated fluxes and mean energies of certain types of particles and photons striking certain components of the following proposed machines: a D-T tokamak reactor (ULFAR-I; MW_e)⁹, a theta-pinch reactor (RTPR; 1440 MW_e)¹⁰, and a D-T-mirror reactor (200 MW_e)¹¹. For lack of space the table does not include such an important tokamak reactor component as a divertor, and the reader is referred to the various recent divertor designs by G. A. Emmert et al.¹², by F. H. Tenney¹³, and by D. Meade¹⁴. While Table 1 gives $\phi(\bar{E})$ -values for some types of particles and photons, it does not list specifically the energy and angular distribution of the various projectiles (particles, photons) impinging on the various reactor components. Especially

the information on photon fluxes (line radiation, bremsstrahlung, and synchrotron radiation) is only fragmentary or nonexistent. The information about $\phi(\bar{E}, \bar{\Omega})$ -values for the other fusion reactor systems shown in Fig. 1 is also very fragmentary. Table 11 lists $\phi(\bar{E})$ -values for one of the major types of projectiles which are estimated to impinge on the first wall of a tokamak experimental power reactor (TFTR-AD, see ref. 15). Information about the angular distribution of the projectiles and about the fraction of plasma particles escaping the plasma region in a neutral charge state is not contained in the table.

Recently, several designs for fusion engineering research facilities (FERF's) have been proposed based on mirror confinement¹⁶, theta-pinch confinement^{17,18}, and tokamak confinement¹⁹. These facilities have first wall loadings of about 1 MW cm^{-2} . The projectile fluxes on the first wall range for deuterium and tritium ions from $5 \cdot 10^{12} \text{ ions cm}^{-2} \text{ sec}^{-1}$ to $7 \cdot 10^{16} \text{ ions cm}^{-2} \text{ sec}^{-1}$, for helium ions from $5 \cdot 10^{13} \text{ ions cm}^{-2} \text{ sec}^{-1}$ to $1 \cdot 10^{14} \text{ ions cm}^{-2} \text{ sec}^{-1}$, and for 14.1 MeV neutrons from $4 \cdot 10^{13} \text{ neutrons cm}^{-2} \text{ sec}^{-1}$ to $1 \cdot 10^{14} \text{ neutrons cm}^{-2} \text{ sec}^{-1}$. The estimated bremsstrahlung power deposition ranges from $\sim 0.04 \text{ Watts cm}^{-2}$ to 1 W cm^{-2} . Again, the energy and angular distribution of the projectiles impinging on the first wall is not well known. For the tokamak fusion test reactor²⁰ (TFTR-TCT) the estimated projectile fluxes per pulse are rather high, but the total number of pulses per year (1000) is moderate. For a pulse length of 0.1 sec. the projectile flux for deuterons and tritons ($E \sim 3-6 \text{ keV}$) is estimated to $\sim 2.6 \cdot 10^{16} \text{ ions cm}^{-2} \text{ pulse}^{-1}$, for helium ions ($E = 3.5 \text{ MeV}$) $3.6 \cdot 10^{12} \text{ ions cm}^{-2} \text{ pulse}^{-1}$, and for 14.1 MeV neutrons $3.7 \cdot 10^{12} \text{ neutrons cm}^{-2} \text{ pulse}^{-1}$.

The above mentioned discussion of various $\phi(E)$ -values should give the reader an appreciation of the wide range of such values for the

various major reactor systems and fusion reactions.

Major Sources for Plasma Contamination

The impact of energetic particles on surfaces can cause such phenomena as physical and chemical sputtering, vaporization, blistering, particle impact induced desorption, secondary electron and x-ray emission, backscattering of reflecting particles, and nuclear reactions. The impact of energetic photons on surfaces can cause photo-desorption, photo-deposition of surface compounds, photo-catalysis leading to a reaction between adsorbed molecules and surface atoms, photoelectron emission, sputtering by the conversion of recoil energy (e.g. by energetic x-rays) into displacement and kinetic energy of recoil atoms, vaporization, and cracking and flaking of insulator surfaces due to photon absorption and the establishment of high temperature gradients in near surface regions.^{2,3} Such surface effects in turn can release major quantities of impurities which will contaminate the plasma. Such impurities released from surfaces have an important effect on the power balance of fusion devices and reactors. For example, the addition of high-Z impurity atoms (or ions) to a D-T plasma will increase the effective charge Z_{eff} of the plasma, where Z_{eff} is given by

$$Z_{\text{eff}} = \frac{1 + \sum_i (n_i/n_{D,T}) Z_i^2}{1 + \sum_i (n_i/n_{D,T}) Z_i} = \frac{1 + \sum_i f_i Z_i^2}{1 + \sum_i f_i Z_i} \quad (1)$$

Here n_i is the impurity atom (ion) density, $n_{D,T}$ is the D-T plasma density (assuming $n_D = n_T$), Z_i is the charge of specie i , and f_i is the impurity fraction of specie i . An increase of the value of Z_{eff} due to an increase

in the values of n_i and Z_i results in a considerable increase in α_i (1), but attracts more the plasma electrons to the $Z_i^{1/2} n_i^{-1/2}$. A value of $Z_{opt} = 9$ would prevent the initiation of a cold D-T plasma without additional power injection.²¹ In the parameters given in the item (1) (1), a moderate impurity density of 0.5% of the D-T plasma would already be sufficient to yield $Z_{opt} = 9$, and to prevent and/or shift additional power injection. Furthermore, heavy impurities tend to diffuse towards the plasma center and collect on the axis of the discharge, and thereby affect seriously the steady-state operation of a reactor.^{24,25} The plasma power loss caused by the presence of high Z impurity atoms does not occur mainly via bremsstrahlung, line, and recombination radiation. If these losses are too high during start-up, they prevent the plasma from ignition, as mentioned above. If these losses increase during plasma operation above critical values, they can cool the plasma temperature below fusion reaction temperatures. For example, for a hydrogen-isotope plasma ($Z = 1$) the ratio R of the power losses due to bremsstrahlung from the plasma with and without a contaminant of atomic number Z_i is given by

$$R = 1 + f_i(Z_i + Z_i^2) + f_i^2 Z_i^3, \quad (2)$$

where f_i is the fractional concentration of the impurity ($f_i = n_i/n_{\text{plasma}}$) of specie i . If one makes the assumption that for the efficient and economic operation of a fusion reactor the increase in the bremsstrahlung losses due to the presence of an impurity should not exceed 20% ($R = 1.2$), the equation (2) can be solved for an upper limit of f_i . For fully ionized impurity atoms, some such limits are $f_{i,m} = 3.6 \times 10^{-4}$ for V, 1.2×10^{-4} for Nb, and 1.1×10^{-4} for Mo. (Note, as mentioned above, $f_i \approx 5 \times 10^{-3}$ for Mo would prevent ignition of a D-T plasma.) For any impurity whose atoms are not fully stripped, the values of $f_{i,m}$ should be kept even smaller than the values

limited object. It is an important part of the surface science studies to identify the source effects which yield sizable high impurity fractions under the operating conditions of plasma devices and reactors.

For an estimate of the number of gaseous impurity atoms released from an irradiated area A in time t it is necessary to know not only the flux $\phi_\mu(\vec{E}, \vec{\alpha})$ of the particular projectile species μ , but also the particle release yield $S_{\mu\nu}(\vec{E}, \vec{\alpha})$ for a particular release process ν given in units of atoms released per incident projectile. In addition, it is necessary to sum over the individual particle release processes ν (e.g. physical and/or chemical sputtering, blistering, photo-desorption, vaporization, particle induced desorption) which can be caused by each particular projectile species μ (e.g., 100 keV de⁺ impact on surfaces can cause physical sputtering, blistering, backscattering of "cooler" primary helium projectiles, and atom desorption).²⁶⁻²⁸ The number of gas atoms released is given by

$$n_i = \sum_{\mu} \sum_{\nu} [\phi_\mu(\vec{E}, \vec{\alpha}) S_{\mu\nu}(\vec{E}, \vec{\alpha})] A \cdot t \quad (3)$$

For estimates of n_i plasma physicists and fusion device design engineers will have to provide more realistic values for the projectile fluxes $\phi_\mu(\vec{E}, \vec{\alpha})$ expected in the operation of different fusion devices and reactors. Surface scientists in turn will have to provide more realistic values for the particle release yields $S_{\mu\nu}(\vec{E}, \vec{\alpha})$ for the various processes ν and types of projectiles μ .

According to equation (3) one of the important factors which determines the number of impurity atoms released is the sum of the yield values for the various particle release processes ν for a given projectile, summed over the various types of projectiles μ , i.e. $\sum_{\mu} \sum_{\nu} S_{\mu\nu}(\vec{E}, \vec{\alpha})$. For many of the particle release processes the $S_{\mu\nu}(E)$ values are known for certain materials.²⁶⁻²⁸

However, for the tokamak reactor and the stellarator configurations (which are still under development), the data available on $S_{\text{p,v}}$ values consist of the information on the [e.g. physical sputtering, chemical sputtering, redeposition, (trapping+emission), particle evaporation, and surface evaporation] is very scanty or nonexistent, and for $S_{\text{p,v}}$ values for these are nonexistent. Information of this kind is especially important for all and composite surfaces (e.g. ceramic and metal coatings of metal components for CTR applications). To what extent synergistic effects due to the simultaneous bombardment of reactor components by high fluxes of energetic particles and photons will affect the $S_{\text{p,v}}$ values is completely unknown. For more detailed reviews of data relevant to the CTR-problem (e.g. physical sputtering, neutron sputtering, blistering) the reader is referred to references 2-8, 29-32.

Solutions to Reduce and/or Eliminate Plasma Contamination

Studies of the control of plasma contamination have been started at several laboratories in this country and abroad.⁸ Some studies are based on design improvements of components (e.g. better cooling of system components such as beam limiters, which receive high plasma power deposition, thereby reducing excessive vaporization). Some other studies center around the development of materials (including coatings) which are of low atomic number, have a low vapor pressure at operating temperature (preferably 10^{-9} - 10^{-10} Torr range), and have low sputtering and blistering yields for the plasma projectile species impinging on them. Other studies deal with improved methods of removing most of the released gaseous impurities before

the energy of the particles (e.g., neutron energy E_n), the mass of the particles m , and the cross section σ of the reaction.

On the other hand, nuclear reactions can be initiated by

low-energy plasma radiation striking the surfaces of structural components of a fusion reactor and a direct ionization process and erosion of the surface of the material thereby limit the lifetime of the irradiated component.

For an estimate of the thickness of material removed in time t , it will be necessary to know not only the flux $\phi_p(\vec{r}, \vec{\Omega})$ of the projectile species p , but also the particle release yield $S_{\text{rel}}(\vec{r}, \vec{\Omega})$ for the release processes caused by projectile species p .

The thickness δ of material removed in time t is given by

$$\delta = \sum_{p=1}^N \frac{1}{N} \phi_p(\vec{r}, \vec{\Omega}) S_{\text{rel}}(\vec{r}, \vec{\Omega}) \cdot t \frac{\lambda}{N}. \quad (4)$$

Here N is the number of atoms in a monolayer and λ is the thickness of a monolayer of the material under bombardment (to a good approximation λ is equal to the atomic diameter or a lattice atom of this material). Equations (3) and (4) cannot describe those synergistic phenomena which lead to nonlinear particle release processes.

At this time useful estimates of the quantity δ are difficult to obtain for the design of the various components of fusion test devices and reactors planned for the next 5 to 15 years (see Figure 1), because the information about the functions $\phi_p(\vec{r}, \vec{\Omega})$ and $S_{\text{rel}}(\vec{r}, \vec{\Omega})$ is insufficient. Some tolerable upper limits for δ for the useful operation of various components exposed to plasma radiations will have to be found. For example, the thickness

loss of a plasma container wall should probably not exceed 25% of its original thickness if it is to maintain its structural integrity. If one accepts some of the recent wall designs⁹ with a thickness of about 3 cm and a desirable wall lifetime of ~ 6 years, the maximum permissible annual thickness loss $\dot{\epsilon}_y$ is 0.1 cm.

Major Sources for Surface Erosion

Some of the major surface effects leading to surface erosion of components by plasma radiations have been identified^{2-4,10,25-28} to be: blistering, chemical sputtering, physical sputtering, neutron sputtering, vaporization, spalling-cracking, photodecomposition (e.g. of insulatory surfaces) and surface embrittlement. The yield data $S_p(E, \vec{i})$ for the individual surface erosion processes listed above are only poorly known for the materials and for the $i_\mu(E, \vec{\alpha})$ values considered for the operation of plasma devices and fusion reactors. In fact, only recently has the importance of radiation blistering and neutron sputtering been fully recognized as potentially serious surface erosion effects during the operation of fusion reactors [e.g. see refs. 2,3,5,7,8,29]. However, a full understanding of the various parameters governing these phenomena is still lacking. A brief review of some recent experimental results on wall erosion due to radiation blistering and neutron sputtering is given in the following.

Radiation blistering

An important surface erosion process has been identified to be radiation blistering.^{2,3,5,7,32} In this process gaseous projectiles

"leaking out" from the plasma region in a charged or neutral state strike exposed surfaces of reactor components. If they penetrate through a lattice with sufficient energy they displace lattice atoms from their sites and are trapped at the end of their range. Near the end of the projected range of the implanted gas atoms, where the gas concentration is at a maximum, the implanted gas atoms combine with vacancies if the permeability of the gas is small (e.g. helium in metals) and form gas filled bubbles. For example, helium bubbles formed at room temperature appear to be nearly spherical and have been observed by transmission electron microscopy to be typically 30-40 Å in diameter.³⁵ At high temperatures, for example for Nb held at 900°C, the helium bubbles are faceted³⁶ and the average diameters range from 250 to 1500 Å. When the density of these bubbles increases with increasing dose, the bubbles interconnect and grow to larger diameters. When the gas pressure within the bubble is high enough, the stresses can be partially released by plastic deformation of the surface skin to form visible blisters. When the stresses exceed the rupture strength for a damaged region, the blisters rupture. The "explosion of gas bubbles" and "stress release" are related phenomena and not two different "mechanisms of blister formation" as stated by some authors.³⁷ The release or bursts of gas from ruptured blisters was first observed mass spectrometrically by the author³⁸ for deuteron bombarded copper. He also observed a pitting of surface regions where blisters had exploded (using surface replica techniques in conjunction with transmission electron microscopy). The bursts of gas released by blister rupture can contaminate the plasma and the peeling of the blister skin can result in serious wall erosion.

Blister formation has been observed for hydrogen isotope

irradiation of Cu,³⁸ Ag,³⁹ Al,⁴⁰ Nb,⁴¹⁻⁴⁴ and Mo.⁴⁵ Blister formation has also been studied for helium-ion irradiation of Nb,^{31,36,41,44-51} V,⁴⁶ V-20% Ti,⁴⁶ Mo,^{45,51,57} Pd,⁵³ and stainless steel.^{31,33,53-56} These experiments have shown that the blister size, shape, and density depend on such parameters as the diffusivity and solubility of the implanted projectiles in the target material, the projectile energy and angle of incidence (affecting the projected range of the projectile in the solid), the yield strength of the material, the target temperature, the dose rate, the total dose, the orientation of monocrystalline target surfaces to the projectile beam, and the initial defect concentration in the target. While at this time a comprehensive blistering theory does not exist and the available experimental data are only fragmentary, certain general trends affecting the erosion of components of fusion devices and reactors under plasma radiations emerge.

For plasma projectile energies larger than about ~ 15 keV the effect of blistering on wall erosion and surface roughening by helium projectiles is considerably more serious for such materials as Nb and V than by hydrogen isotope projectiles for comparable flux levels. For example, for 0.5-MeV deuteron bombardment of cold-worked niobium to a total dose of 1.0 Coulomb/cm^2 at room temperature no visible blisters could be resolved.^{3,41} For the corresponding case for helium bombardment a large number of blisters per unit area was observed⁴⁷ with a large distribution in the blister size. In order to observe blisters by deuterium implantation in cold rolled niobium it was necessary to raise the target temperature. For example, for 0.25 MeV D^+ irradiation of niobium held at 700°C to a total dose of 1.6 C/cm^2 Donhowe and Kulcinski³⁷ and Kaminsky and Das⁴¹ observed blisters with an average blister diameter of $0.72 \mu\text{m}$ and $0.4 \mu\text{m}$, respectively.

The significant difference in the blistering of niobium under helium and deuterium bombardment under otherwise identical irradiation conditions can be related to the large difference in the solubility and diffusivity of these gases in niobium. For example, the diffusion coefficient of deuterium in niobium is $D_D = 1.3 \times 10^{-4} \text{ cm}^2/\text{sec}$ at 800°C , while that for helium in niobium varies from 10^{-19} to $10^{-14} \text{ cm}^2/\text{sec}$ between the temperatures of 600°C and 1200°C .

Figs. 2a to 2f (taken from ref. 31) illustrate the effect of projectile energy on helium blister formation in niobium irradiated at room temperature. Irradiation to a dose of 0.5 C/cm^2 with $100 \text{ keV } ^4\text{He}^+$ ions results in a blister density of $\approx 2 \times 10^6 \text{ blisters/cm}^2$, and the average blister diameter ranges from 1 to $30 \text{ }\mu\text{m}$ (fig. 2a). Many of the large blisters show exfoliated skins and in some cases a second blister skin has ruptured and fallen off. Fig. 2b shows an enlarged view of a blister skin from which the skin thickness can be estimated to be $\approx 0.38 \text{ }\mu\text{m}$. Irradiation with $250 \text{ keV } ^4\text{He}^+$ ions to the same dose of 0.5 C/cm^2 showed blisters with average diameters ranging from 3 to $30 \text{ }\mu\text{m}$, and the blister density was $\approx 1.2 \times 10^6 \text{ blisters/cm}^2$. For $0.5 \text{ MeV } ^4\text{He}^+$ ion irradiation to a total dose of 1.0 C/cm^2 a very large blister (fig. 2c) occupied about two-thirds of the bombarded area. From an enlarged view of a portion of the ruptured skin shown in fig. 2d the skin thickness is determined to be $\approx 1.1 \text{ }\mu\text{m}$. On further increase of the projectile energy to 1.5 MeV only one large blister occupied the entire bombarded area (fig. 2e). A portion of the ruptured skin can be seen in fig. 2f and the skin thickness is found to be $\approx 2.9 \text{ }\mu\text{m}$. From a comparison of the blister skin thicknesses for different helium ion energies (figs. 2b, 2d, and 2f) it is clear that the blister skin thickness is increasing with increasing projectile energy.

The increase in blister size with increase in projectile energy can be understood if one considers the expressions for the gas pressure p inside a blister as discussed earlier.⁴⁷ The pressure p is directly proportional to the skin thickness t and inversely proportional to the square of the radius a of the blister. Hence, for a given blister height h and pressure p (which is roughly proportional to the total dose), a higher projectile energy (and correspondingly higher skin thickness t) will require a larger blister radius a . At high temperature (e.g., niobium at 900°C) the effect of projectile energy on blister size is less pronounced. It should be pointed out that the erosion rates S estimated by techniques described earlier^{46,47} for 100 keV and 0.5 MeV helium ion irradiations (see figs. 2a and 2c, respectively) yield values of $S \approx 1.0 \pm 0.4$ and $S \approx 0.20 \pm 0.05$ niobium atoms per incident helium ion, respectively. Such an increase in erosion rate with decreasing projectile energy has also been observed for Type 304 stainless steel^{33,54} for the energy range studied. The question if blisters rupture near the region of maximum concentration of implanted gas or near the region of maximum lattice damage (taken to be the region of the maximum in the damage-energy distribution) was recently answered for the blistering of Nb by He ions for the energies 100, 250, 500, 1000, and 1500 keV.⁵⁸

Figure 3 illustrates the correlation between the measured skin thicknesses [Fig. 3A, (a)-(e)], the damage-energy distribution (solid curves in Fig. 3B), and the projected-range distributions (dashed curves in Fig. 3B) for the helium-ion energies of 100, 250, 500, 1000 and 1500 keV. The distributions in Fig. 3B were obtained using the tabulated projected range, straggling and damage-energy values for helium ions incident on Zr and Ag using Brice's interpolation method.⁵⁹ These tabulated values for damage-energy

distributions were calculated using an intermediate method developed by Brice⁶⁰ which includes the spatial distribution of the energy transferred by primary recoil atoms. The total error in the calculation of the projected-range distribution, damage-energy distribution and in the interpolation was estimated to be 12%.⁶¹

The present results reveal that the average skin-thickness values correlate more closely with the maxima in the projected-range distributions than with the maxima in the damage-energy distributions. This result implies that for niobium irradiated with helium ions in the energy range studied the blister skin separation from the bulk occurs near the region of maximum helium concentration rather than near the region of maximum lattice damage, in accordance with the model for blister formation and rupture formulated earlier by Kaminsky and Das.^{41,47}

The target temperature is one of the important parameters affecting blister formation and blister rupture. The temperature affects the critical dose for blister appearance and the exfoliation of blisters and thereby the erosion rates. For example, for helium bombardment of annealed polycrystalline niobium at room temperature for a total dose of 0.1 C/cm^2 no blisters could be detected,³¹ but blisters were readily detected for 900°C irradiation even after a dose of only 0.01 C/cm^2 .^{48,49}

Figures 4a, 4b, and 4c illustrate blisters formed in polycrystalline vanadium during irradiation at different temperatures with $0.5\text{-MeV } ^4\text{He}^+$ ions for the same dose of 1.0 C/cm^2 . For room temperature irradiation many irregularly shaped blisters were observed (Fig. 4a). The blister skin had ruptured and fallen off at many places. The average diameters of the blisters range from 15 to $350 \mu\text{m}$. Irradiation at $600 \pm 20^\circ\text{C}$ revealed (Fig. 4b) a very large blister that covered most of the irradiated

area. The blister had ruptured and three exfoliated skin layers can be seen as compared to only one in Fig. 4a. Approximate values of the erosion rates were determined directly from micrographs, such as in Figs. 4a and 4b, by measuring the skin thickness and the area from which the skin has fallen off, as described earlier.⁴⁷ The erosion rates estimated in this way are 0.10 ± 0.03 and 0.20 ± 0.05 vanadium atoms per incident helium ion for room temperature and for $600 \pm 20^\circ\text{C}$ irradiations, respectively. Irradiation at $900 \pm 20^\circ\text{C}$ produced blisters of considerably smaller size (Fig. 4c). The blisters have average diameters of 10 to 20 μm and occupy only about 1.7% of the total irradiated area. The large-scale exfoliation of the blister skin observed at $600 \pm 20^\circ\text{C}$ (Fig. 4b) is not seen at $900 \pm 20^\circ\text{C}$ (Fig. 4c).³³ Fig. 5A shows a plot of the erosion rates versus target temperature for helium blistering of Type 304 stainless steel. It can be seen in fig. 5A that the maximum erosion rate occurs at an irradiation temperature of $\approx 450^\circ\text{C}$. A qualitatively similar temperature dependence has been observed for Type 316 stainless steel.⁵⁵ Another striking result that is apparent from fig. 5A is that as the projectile energy is reduced from 0.5 MeV to 100 keV the erosion rate increases by approximately a factor of 7 for the same dose of 0.5 C/cm^2 and a temperature of $\approx 450^\circ\text{C}$. Fig. 4B shows the effect of temperature on the blister formation in polycrystalline vanadium irradiated with 0.5 MeV $^4\text{He}^+$ ions for the same dose of 1.0 C/cm^2 . The erosion rate appears to be at a maximum somewhere between 300°C and 500°C .

The observed change in erosion rates with temperature is related to the strong temperature dependence of the yield strength of the material. For example, the yield strength of annealed 304 stainless steel at 450°C is half of its value at room temperature. Similarly the tensile strength of annealed vanadium at 900°C is less than a third of its value at

room temperature. Thus, for a particular dose the collected gas in a bubble can deform the surface skin more readily at high temperature (e.g. stainless steel at 450°C) than at room temperature. In addition, the kinetic pressure of the gas in the bubble will increase with temperature and may also enhance this process. However, at very high temperature (e.g. at 900°C for vanadium) helium may be released through the surface either by atomic diffusion or by migration of small bubbles. Some recent work⁶² shows that helium bubble mobility in niobium at 950°C is at least two orders of magnitude higher than that calculated earlier by Martin.⁶³ Mass spectrometric evidence for helium release from niobium, vanadium and 316 stainless steel has been reported.^{35,55} Therefore, the amount of helium trapped in the lattice will be affected by the helium release rate and the bubble nucleation rate and will in turn determine the size and density of helium bubbles and the subsequent blister size. Thus the degree of blistering and exfoliation of blister skin is maximized if the temperature is high enough so that the surface can be deformed easily (lower yield stress) but low enough so that the helium release from the surface is still very small.

It has been observed^{36,41,48} that for helium-ion irradiation of niobium the blister size increases with increasing total dose. Figs. 6a, 6b, and 6c show blisters formed in Type 304 stainless steel irradiated at 450°C with 0.5-MeV $^4\text{He}^+$ ions to total dose of 0.1, 0.5 and 1.0 C/cm², respectively. For a dose of 0.1 C/cm² the single observed blister diameter is $\approx 700 \mu\text{m}$ (fig. 6a) and a large portion of the irradiated area is occupied by this single blister. At a higher dose of 0.5 C/cm² three exfoliated skin layers are observed (fig. 6b, as compared with one for a dose of 0.1 C/cm² (fig. 6a). For an even higher dose of 1.0 C/cm² the number of exfoliated

layers increases to five in some regions (fig. 6c). The estimated erosion rates for the three doses 0.1, 0.5 and 1.0 C/cm² are 0.1 ± 0.05 , 0.45 ± 0.1 and 0.8 ± 0.2 atoms per incident ion, respectively. One should note that within the experimental error the erosion rates depend nearly linearly on the dose in the dose range studied. One should keep in mind that these rates are determined only from that part of the blister skin which has been totally lost. Therefore the observed increase in the erosion rates with increasing dose (for the dose range studied here) is related to the increase in the exfoliation of blisters and to the subsequent loss of blister skin with increasing dose.

The effect of total dose on the blister size is less pronounced at high target temperature (e.g., Nb or V at 900°C) than at room temperature.^{41,42} For example, for annealed polycrystalline vanadium irradiated at 900°C with 0.5 MeV ⁴He⁺ ions one observes that as the dose is increased by one order of magnitude from 0.1 to 1.0 C/cm² the mean value of the average blister diameters shows⁴² only a slight increase from 6.2 to 7.4 μm. This is in part due to a higher rate of helium release at 900°C than at room temperature³⁵ as mentioned above.

At a particular irradiation temperature the rate of gas buildup near the implant depth and the subsequent blister formation will depend on the dose rate (i.e. the incident ion flux) and the rate of gas release from the surface. Depending on the balance of gas trapping and gas release, there may or may not be an effect of dose rate on blister formation. Recent results on blistering in helium-implanted vanadium show⁴² that with increasing dose rate from 1×10^{13} to 1×10^{15} ions/(cm² · sec) the blister density increases from $(1.0 \pm 0.5) \times 10^4$ to $(7 \pm 2) \times 10^4$ blisters/cm². For deuterium blistering in

niobium the effect of dose rate is found to be much more pronounced than for helium blistering for similar irradiation conditions.⁴² An increase in the dose rate has also been observed⁶⁴ to reduce the critical dose for blister formation in proton-irradiated molybdenum.

In addition to the parameters discussed above there are many other parameters that affect the degree of blistering and only a few will be mentioned here. Recent experiments³⁶ on helium blistering in cold-worked and annealed niobium and vanadium show that for room-temperature irradiation the blister size and the degree of blistering is reduced by cold working. Cold working has also been observed to reduce the void number density in neutron-irradiated stainless steel,⁶⁵ but the void size does not change very much. However, for irradiation at 900°C, the degree of blistering is similar for cold-worked and annealed samples for both vanadium and niobium, because 900°C is within the annealing temperature range for vanadium and for niobium.

In bombarding monocrystalline metals with helium ions or deuterons, it has been observed^{41,50} that the blister shape and the orientation of the blisters with respect to each other depend strongly on the crystallographic orientation of the irradiated surface plane of the target. The shapes of blisters formed on the (111), (110) and (001) surface planes of monocrystalline niobium samples irradiated at 900°C with axially channeled 0.5 MeV $^4\text{He}^+$ ions have been related to the intersection of certain active slip planes with the surface plane of the monocrystal during blister formation.^{49,50} For example Fig. 7a-7d shows secondary-electron scanning electron micrographs of (111) Nb monocrystal surfaces after irradiation with 0.5-MeV He^+ to a total dose of 1.0 C/cm^2 , (a) at 900°C, He ions well channeled along the [111] axis (beam direction was within 0.1° parallel to [111] axis), (b) at 700°C and same channeling conditions as under (a), (c) at 20°C and same

channeling conditions as under (a), (d) at 900°C, He ions de-channelled (beam direction was 5° off the [111] axis).⁴⁸⁻⁵⁰ The blisters shown in Fig. 7a appear to have distinct crystallographic features, including facets on the surface. Purposely putting a reference scratch mark on a small area of the surface made it possible to do single-surface trace analysis from the back-reflection Laue diagrams. It was found that the prongs of the crowfoot-shaped blisters are aligned rather perfectly along the traces of {110} planes of the host niobium lattice as shown in Fig. 7(a). Thus most of the blisters exhibiting trifold symmetry on the irradiated (111) surface plane have been formed by three prongs joining at the [111] pole as the blister center. The blisters appear to be very uniform in size. Measurements of each blister from the center to the end of a prong give a length of about 1.5-2.0 μm , and the maximum width of a prong ranges from 0.7 to 0.9 μm . Isolated single prongs that have not joined to give the trifold symmetry also have dimensions that fall within the above mentioned ranges. The average blister density is about 3×10^6 blisters/ cm^2 . Some surface irregularities of unidentified nature are seen in certain small regions, but these vanish completely when the surface is ion milled lightly by argon-ion sputtering, while the shapes and sizes of the blisters remain nearly unchanged. At 700°C both dome-shaped and crowfoot-shaped blisters form (Fig. 7b). At 20°C only dome-shaped blisters form (Fig. 7c). For the non-channelled beam case (Fig. 7d) the blister density is now approximately 8×10^8 blisters cm^{-2} , more than two orders of magnitude greater than for the channelled case (Fig. 7a). These results show that the size and shape of the blisters change with the degree of channeling and irradiation temperature. In comparison to the unchanneled case, well-channelled helium ions incident on a (111) surface of a monocrystal introduce much less

radiation damage near the surface; the peaks of the damage distribution and the concentration of implanted ions shift to larger depths below the irradiated surface. Although the maximum range of 0.5-MeV ^4He ions well channeled in the $\{111\}$ direction is not known experimentally, it is expected that the mean linear range of channeled ions will be substantially greater than that for a nonchanneled beam. With channeled ions, therefore, far fewer bubbles are nucleated close to the surface and the degree of blistering is reduced; moreover, the observation that blister progs are oriented only along the traces of $\{110\}$ planes may give a clue to the nucleation of helium bubbles. In bcc niobium, the maximum interplanar spacing is between the $\{110\}$ planes. This may allow the helium atoms to accumulate more readily along these planes to form bubbles later on.

Finally, it should be pointed out that the observed erosion rates for 0.5-MeV helium blistering for V at 500°C (~ 0.6 atoms/ion) and for 304 stainless steel at 450°C (~ 0.75 atoms/ion) are more than two orders of magnitude larger than the estimated sputtering yields² for helium bombardment under identical irradiation conditions. In fact the blistering erosion rate for 304 stainless steel at 450°C for 100-keV helium bombardment to a dose of 0.5 C/cm^2 (~ 3 atoms/ion) is nearly two orders of magnitude larger than the estimated combined sputtering yields for 25-keV D^+ , T^+ , and 100-keV He^+ .² Therefore blistering by energetic helium projectiles is a more effective surface erosion process than physical sputtering by deuterons, tritons and helium ions for comparable energy ranges. From the erosion rate for the 304 stainless steel for 100 keV He^+ ion irradiation to a total dose of 0.5 C/cm^2 at 450°C an annual thickness loss of about $\Delta = 0.09 \text{ mm}$ per year can be estimated for a helium-flux of $1 \times 10^{13} \text{ projectiles cm}^{-2} \text{ sec}^{-1}$.

This value alone approaches the maximum allowable annual thickness loss mentioned in the introduction, and other processes such as physical and chemical sputtering, and vaporization of the blister skin due to energetic photon absorption will also contribute to the erosion rate.

Solutions to Reduce or Eliminate Surface Erosion by Radiation Blistering

At this time only a few studies have been started to find methods to reduce the surface erosion by the various erosion processes such as helium blistering and chemical and physical sputtering. For example, one possible way to reduce surface erosion due to helium blistering in fusion reactor components is to maintain the surfaces at a high enough temperature (e.g. $> 900^{\circ}\text{C}$ for Nb and V) so that some of the implanted helium is released without forming large bubbles.^{31,33} However, the operating temperatures of various components may be limited by other design criteria. A more desirable solution would be to choose a material with a microstructure which minimizes the formation of blisters. A promising class of materials appears to be sintered metal powder with small average grain sizes and of low atomic number Z.^{66,67} Initial studies of the surface erosion of sintered aluminum powder (SAP) and of aluminum due to blistering by helium ions (100 keV, dose 1.0 C/cm^2) reveal a reduction in the erosion rate in SAP by more than three orders of magnitude as compared to the erosion rate of pure aluminum.⁶⁷ There are several factors that may be responsible for the drastic reduction in the erosion rate due to blistering in SAP as compared to pure aluminum. The average grain size of SAP used in the studies was $\sim 0.5 \mu\text{m}$ while that of annealed aluminum had an average grain size of $\sim 300 \mu\text{m}$. Thus the large grain-boundary area in SAP, which

is more than 5 orders of magnitude larger than the one for the aluminum used here serves as a very effective sink for vacancies. The effect of grain refinement on reduction in void swelling has been observed in electron-irradiated dispersion-hardened stainless steel. To what degree the increase in grain-boundary area will effect the helium trapping or cause an enhanced helium release through the grain boundaries cannot be stated at this time.

Neutron Sputtering

The erosion of surfaces due to physical and chemical sputtering, caused by energetic ion and atom impact will not be covered in the following since detailed discussions have appeared elsewhere.^{2-5, 27, 28} Instead we will describe some recent discoveries on neutron sputtering.

During the operation of large steady-state D-T-fusion reactors of the size envisioned by Kulcinski et al⁹, high fluxes of 14-MeV neutrons penetrate the first wall (see Table 1). In addition "backstreaming" neutrons from the blanket region [e.g. neutrons from (n,2n) reactions, and backscattered neutrons] with energies less than 14 MeV will also penetrate the first wall. Such high fluxes of energetic neutrons with the neutron energy spectrum characteristic of a D-T fusion reactor represent a substantially different neutron irradiation environment than that of a fission reactor. Therefore, the author suggested^{2,3} that various mechanisms leading to particle release and surface erosion under neutron impact (e.g. energetic collision cascades, heated spikes, "ionization" spikes) will be more effective in a fusion reactor than in a fission reactor contrary to some recent speculations by others.⁴

The experimental and theoretical information available on neutron sputtering has been very scarce and contradictory (for reviews see ref. 2-4,7,32).

The experiments by Kaminsky et al^{7, 32, 68-70} were undertaken to provide information on the erosion of surfaces of cold rolled and annealed polycrystalline metals (e.g. Nb, V) and of SiC with various surface finishes under 14-MeV neutron bombardment. The samples were irradiated at room temperature with 14-MeV neutrons from the Lawrence Livermore Laboratory's rotating target neutron source to total doses of $4-5 \times 10^{15}$ neutrons cm^{-2} , depending on the position of the sample with respect to the source. The samples were kept in an ultrahigh vacuum, $\sim 2 \times 10^{-9}$ Torr at the beginning of a run and $\sim 1 \times 10^{-9}$ to 5×10^{-10} Torr by the end of a run. The type and the amount of the material released from one sample and deposited on the surface of a sample placed opposite was determined with the aid of Rutherford backscattering (~ 0.0005 ML), secondary ion microprobe (~ 0.001 ML), Auger spectroscopy (~ 0.01 ML), and a scanning electron microscope in conjunction with an energy-dispersive x-ray spectrometer which had been calibrated with standards and blank samples. The detection sensitivities of some of these techniques are listed in brackets as fractions of a monolayer (ML) of niobium deposited on a silicon substrate. For more experimental detail see refs. 7, 32, 68-70. A total of ten independent neutron irradiation runs were performed and for each type of cold rolled target at least two independent irradiations were made. The observations reveal several striking and important results:

(1) The deposits of such materials as Nb, V, stainless steel and SiC appear in two forms (a) One form covered the substrate surface in atomic form as a fractional atomic layer as is commonly observed in ion sputtering. (b) The other form was discovered^{7, 32, 68} as chunks of various sizes and irregular shapes (Fig. 8). The emission of chunks had not been observed in ion sputtering experiments and was not anticipated by any existing sputtering theory. Cafasso et al⁷¹

have recently confirmed by independent measurements the ejection of niobium chunks from 14-MeV neutron irradiated polycrystalline niobium. The scanning electron micrograph (backscattered electron image) in Fig. 8a shows a niobium chunk. Fig. 8b shows an x-ray energy spectrum of the chunk where only Nb L and Al K peaks can be identified. (Note, the niobium has been deposited on an aluminum substrate.) The niobium L x-ray image shown in Fig. 8c was obtained for the same area with the energy dispersive x-ray spectrometer and it confirmed that the chunks were niobium. A secondary ion ($^{93}\text{Nb}^+$) micrograph of the niobium chunk is shown in Fig. 8d which further confirms that the chunk is niobium. For the case of the irradiated cold-rolled polycrystalline niobium target we reported earlier^{32,68,69} that the larger fraction of the chunks appeared more spherical in shape and the smaller fraction appeared to be more cylindrical in shape. For the case of the vacuum-annealed polycrystalline niobium targets, however, no cylindrically shaped chunks could be observed.

(2) Both types of deposits are not uniformly distributed over the collectors area but are clustered along certain streaks or appear in certain patches; sometimes both types of deposits (fractional atomic layer and chunks) appear clustered on certain substrate areas. For example, as illustrated in Fig. 9, the deposits can appear as wide streaks (width > 40 μm , lengths > 400 μm) which are not associated with the microstructure of the substrate structure. The direction of the streaks appears to be parallel with the direction of the cold-rolling of the niobium sample. Fig. 10 shows the surface structure of a cold-rolled sample (lightly electropolished) with a coarse surface finish of $\sim 5\mu\text{m}$. The deposits also appear in irregularly shaped patches. The appearance of streaks and patches is much more pronounced for the cold-rolled niobium sample than for the vacuum-annealed samples.

(3) The number of chunks, their size and shape depend very strongly on the tensile stresses in the surface regions (e.g. due to cold rolling), and on the degree of microstructure of the irradiated surface (e.g. microprotrusions, microcracks) as illustrated by the values listed in Table 3 for Nb targets and total neutron fluences ranging between $4.2-4.8 \times 10^{15}$ neutrons/cm². The table lists for each type of target ranges of chunk deposit density values (number of chunks per cm²) which indicate the smallest and the largest number of chunks which can be found on a contiguous surface area of 1 cm² within the total collector area indicated in the table. The chunk density values for the repeat runs fall within the ranges listed. The range of values listed in Table 3 reveals the strong non-uniformity in the distribution of chunks on the collector surface, and also the fact that the ejection of chunks is a relatively rare event in comparison to the total number of primary knock-on events produced by 14-MeV neutrons in near surface regions.⁷² However, even a few chunks of micron size can contribute more to the total deposition than the atomically deposited material, as will be discussed later. The results also illustrate that the chunk ejection can be reduced or eliminated if the tensile stresses in near surface regions are reduced (e.g. high vacuum anneal, monocrystalline target) and if the surface smoothness is improved. The observed sizes of chunks vary from $\sim 0.05 \mu\text{m}$ to $\sim 5 \mu\text{m}$ in "average diameter",^{7,32,68-70} the larger-size chunks ($> 1 \mu\text{m}$) are observed for the cold-worked samples having the roughest surface finish.

(4) The average velocity of the chunks has been estimated³² to be $\bar{v} \leq 10$ cm/sec. For chunks with a mass of $\sim 8 \times 10^{-11}$ gm and $\bar{v} = 10$ cm/sec, the value of the kinetic energy is $E = 4 \times 10^{-9}$ ergs, a value which would correspond to about 0.5% of the energy deposited by a 600 keV recoiling Nb atom, or about 1% of the damage energy. As pointed out earlier^{7,68,70}

the stored energy per chunk volume (e.g. due to cold rolling) can be several orders of magnitude higher (the order of 10^{-4} ergs per chunk volume) than the energy deposited by the primary recoil.

(5) Measurements of the concentration profile of the fractional atomic-layer deposit by Rutherford backscattering (beam diameter $\sim 300\mu\text{m}$) and ion microprobe (beam diameter $\sim 25\mu\text{m}$) reveal that the deposit concentration varies from a low value of $< 5 \times 10^{-4}$ ML to a high of $\sim 2 \times 10^{-2}$ ML in patch and streak regions near chunks. It should be pointed out that even for the case of maximum chunk deposits, areas of $10\text{-}30 \text{ mm}^2$ can be found on the collector surface with an "average" deposit concentration of $< 5 \times 10^{-4}$ ML.

The following working model for chunk emission has been suggested by Kaminsky et al.³². The observation that the number of deposited chunks decreases as the stresses in near surface regions decrease and as the surface finish improves suggests that the amount of stored energy (e.g. due to cold working) and the degree of microstructure of the irradiated surface (e.g. microcracks, scratches, protrusions) affects the chunk emission significantly. The energy deposited by a 14-MeV neutron interacting with niobium lattice atoms via elastic and inelastic collisions (calculated mean and maximum energies for primary knock-on niobium atoms are 180 and 600 keV, respectively) can lead to localized thermal and ionization (electron) spikes. The thermal spikes in turn may cause the generation of shock waves in times of the order of 10^{-13} sec. The interference of such shock waves in a small volume in near surface regions in which the stored energy is very high may trigger the release of existing stresses by initiating submicroscopic cracks or by propagating already existing microcracks, and cause the emission of chunks from highly stressed and rough surface regions. In addition, microprotrusions with only a small fraction of the surface atoms bound to the host lattice may

also be released by such an energy release mechanism. A recently developed model of chunk emission by Gaium⁷² incorporates some aspects of this working model and shows that the emission of chunks from stressed niobium surfaces under 14.1 MeV neutron bombardment is probable.

It is not surprising that existing sputtering theories cannot account for the observed chunk emission since they fail to take into account the stored energy in the crystal surface region and the surface microstructure. For a review of such "deficient" sputtering theories see ref. 73. The observation that even the fractional atomic layer deposit is somewhat higher (e.g. for an etched, cold-rolled Nb surface with a 5 μ m average surface finish the observed sputtering yield for the fractional atomic layer deposit ranges from $\sim 2 \times 10^{-4}$ to 6×10^{-4} atoms per neutron) than calculated from existing sputtering theories (based on collision cascade models only) (e.g. the calculated 14-MeV neutron sputtering yield for Nb was $\sim 6 \times 10^{-5}$ atoms per neutron - see refs. 2,3) may in part be related to the release of atoms and atom clusters not only via collision cascades (and correlated collision cascades) but also via thermal spike triggered particle release. To what extent recent observations by other authors⁷⁴ of no chunk emission from cold-rolled niobium foils under 14-MeV neutron bombardment can be related to differences in surface stresses and surface finishes of the samples or to differences in the detection techniques cannot be answered readily at this time.

At this time accurate estimates of the total sputtering yield for the range of neutron fluences used are very difficult to obtain for the rough, cold-rolled niobium surfaces. Firstly, since the chunk emission appears to be a very rare event, the available statistics on chunk deposit density for a given type of niobium target is extremely poor. Secondly, the size distribution of the chunks is also only poorly known. However,

even small changes in the average values of such the distribution into the calculated volume ($\sim r^3$), and thereby the work of the erosion chunk. Therefore, only very crude estimates of total neutron sputtering-yield values can be made. For example, for a cold-rolled, lightly electropolished niobium surface with a 5- μ m surface finish, the more probable sputtering-yield values S_n for the fractional atomic-layer deposit (often called "background" signal) range from $\sim 2 \times 10^{-5}$ to 6×10^{-4} atom/neutron, but in certain areas near streaks and patches values as high as 8×10^{-5} atom/neutron have been observed. To what extent this relatively high-yield value is due to the deposition of atomic clusters and "mini"-chunks with sizes below the detection ability of the scanning electron microscope used ($\sim 100 \text{ \AA}$) cannot be stated at this time. The sputtering-yield values from the contribution of chunks to the niobium deposit can also be estimated only very crudely. For example, for a cold-rolled, lightly electropolished niobium surface with a 5- μ m surface finish a lower and upper limit yield value S_c can be estimated from the lower and upper limit values for the chunk deposit density and the chunk-size distribution for the more probable range (see table 3). Based on these values a range of S_c values can be given, $0 \leq S_c \leq 1.1 \times 10^{-3}$ atoms per neutron. For the case of the largest chunk deposit density ever observed (~ 1000 per cm^2), the value would be $S_n = 3.7 \times 10^{-2}$ atoms per neutron. The recently quoted high value of $S_n = 2.5 \times 10^{-1}$ atoms per neutron⁶⁸ assumed a higher average chunk size value ($r = 1.7 \mu\text{m}$) than the ones used above for the lower and upper limit values (based on somewhat improved statistics in determining the chunk size distribution of the few chunks observed). Such a high yield value of 0.25 ± 0.1 niobium atom per neutron would lead to an annual erosion $i_y = 0.6 \text{ mm}$ per year for a 14.1 MeV neutron flux of 4×10^{14} neutrons $\text{cm}^{-2} \text{sec}^{-1}$,

if one assumes that equal amounts of material ($\approx 0.3\text{mm/year}$) are lost from each side of the first wall of a fusion reactor. Kuicinski et al.⁹ pointed out that under such conditions almost two thirds of the total wall erosion of a tokamak fusion reactor (ITER-94 - ref. 9) would then be due to such high energy neutrons. However, if a total yield of 1.7×10^{-3} atoms per neutron is more typical for such rough cold rolled surfaces, then the annual erosion rate for the neutron flux mentioned above would be only $i_y = 4 \times 10^{-3}$ mm per year, an acceptable value from the surface erosion point of view. (The contribution of chunk emission to the plasma contamination has not been evaluated yet.) More neutron sputtering experiments on rough surfaces of candidate materials for fusion reactors need to be conducted for large surface areas and for increased neutron fluences in order to increase the number of chunk emitting events and thereby improve the statistics. The author speculates that the number of chunks emitted will not increase with neutron fluence over a broad range of neutron fluences. The reason is that once the stress risers in near surface regions have been released, the surface will have "aged", and without the build-up of new stresses will not have localized stressed regions suitable for chunk emission.

Solutions to Reduce or Eliminate Surface Erosion by Neutron Sputtering

The author has suggested earlier⁷ that a sacrificial wall of a low-Z material (e.g. SiC, graphite), well annealed with a high melting point and a smooth surface finish, may help significantly to reduce plasma contamination and erosion of the vacuum container wall due to neutron sputtering and blistering. This wall liner should be properly placed between the plasma region and the vacuum container wall to absorb most of the plasma

released particles (except neutrons) and photons. Its operating surface temperature should be high enough to reduce surface roughening and erosion due to blistering, and to keep the surface regions well annealed. This in turn will help to reduce neutron-impact-induced chunk emission on the surface facing the plasma, and thereby plasma contamination.

The stressed vacuum wall, of course, will be subjected to erosion by neutron sputtering on both sides.² However, with proper choices of materials (less brittle materials) and with high surface finishes one should be able to reduce erosion due to chunk emission to reasonable levels.

At this time it is difficult to assess to what degree the pitting of the surface due to chunk emission will enhance the corrosion of the side of the wall which is in contact with the metal coolant.

Additional techniques which need to be explored to reduce surface erosion will include (1) choice of low Z materials with low sputtering and blistering yields and high melting points, (2) choice of proper surface structures (e.g. porous surface for low gas trapping), (3) proper design of components, (4) tailoring of plasma radiations (e.g. divert charged component to collector plates), (5) ionization (and subsequent diversion) of wall released impurities with the aid of an electron sheath which exists in near surface regions of irradiated components (proposed in ref. 2), (6) use of a purging gas, and (7) auxiliary electrical and magnetic fields which help to prevent charged plasma radiations from striking in localized areas ("hot spots"). In order to reduce wall erosion not only the application of techniques (1) - (4) may help, but also the use of multiple and/or rotating limiters,⁷⁵ and sacrificial walls (liners).

CONCLUSIONS

The surface science data needed for the development of fusion power in the U.S. will require during the next 15 to 20 years studies of the yield values for the various individual particle emission phenomena relevant for the plasma parameters and the materials envisioned for CTR applications. In addition, studies of synergistic effects due to the simultaneous bombardment of surfaces by high-fluxes of energetic particles of various types and photons will have to be started. Only with the proper identification and understanding of the most deleterious effects will it become meaningful to develop methods to reduce and possibly eliminate serious plasma contamination and wall erosion.

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Table 1. Particle and Photon Interactions with Components of Fusion Reactors or Devices (taken in part from ref. 7)

		First Wall		Direct Converter Expander		Direct Converter Collector	
		Flux ($\text{cm}^{-2} \text{sec}^{-1}$)	E_m , Mean Energy (KeV)	Flux ($\text{cm}^{-2} \text{sec}^{-1}$)	E_m , (KeV)	Flux ($\text{cm}^{-2} \text{sec}^{-1}$)	E_m , (KeV)
D-T Tokamak Reactor							
UWMAR-I (1,500 MW _e) (G. L. Kulcinski et al ⁹)	D ⁺	6.4×10^{13}	23				
	T ⁺	6.4×10^{13}	23				
	He ⁺	4.7×10^{12}	23				
	He ⁺⁺	1.7×10^{11}	~100	not applicable		not applicable	
	n	9.4×10^{13}	$E_m > 10^4$				
	Bremsstrahlung	3.4×10^{14}	$100 < E_m < 10^4$				
D-T Theta Pinch Reactor							
RTPR (1,440 MW _e) (R. A. Krakowski et al ¹⁰) burntime: 0.06 sec, plasma cooling time: 1.3 sec, duty cycle: 10.0 sec	n averaged	1.7×10^{14}	1.4×10^4				
	n averaged	6×10^{14}	$100 < E_m < 1.4 \times 10^4$				
	Bremsstrahlung	71.62J / (cm ² pulse)	wavelength range ~ 5-1.0 μ	not applicable		not applicable	
	plasma fuel particle flux	not specified	not specified				
	plasma ash particle flux	not specified	not specified				
D-T Mirror Reactor							
(200 MW _e) (J. D. Lee ¹¹)	D ⁺	5.3×10^{14}	550	3.2×10^{15}	610	4.3×10^{13}	100
	T ⁺	3.2×10^{14}	580	1.9×10^{15}	640	2.5×10^{13}	100
	He ⁺⁺	3.5×10^{13}	1200	2.1×10^{14}	1300	2.1×10^{12}	200
	n	8×10^{13}	1.4×10^4				
	Bremsstrahlung	2.6 W/cm ²	x-ray energy range				
	Synchrotron radiation	225 W/cm ²	far infrared energy range				

TABLE 2

Particle and Photon Interactions with the First Wall
of a Tokamak Experimental Power Reactor
(TEPR-100, 5-50 MW_e, ref. 15)

Projectile Species	Flux, ϕ , projectiles $\text{cm}^{-2}\text{sec}^{-1}$	Mean Energies, $\bar{E}$, or Energies Spectrum
Fast neutrons	1×10^{13}	$\bar{E} = 14.1 \text{ MeV}$
Total neutrons	4×10^{13}	$1 \text{ ReV} < E < 14.1 \text{ MeV}$
Fast helium	7×10^{11}	$\bar{E} = 7.5 \text{ MeV}$
Slow helium	1×10^{13}	$\bar{E} =$ most probable $\sim 10 \text{ keV}$, Maxwell distribution
Deuterium	5×10^{14}	$\bar{E} \sim 10 \text{ keV}$, Maxwell Distribution
Tritium	5×10^{14}	$\bar{E} \sim 10 \text{ keV}$, Maxwell Distribution
Bremsstrahlung	1 Watt cm^{-2}	$\bar{E} \sim 10 \text{ keV}$, Boltzmann Distribution
Synchrotron Rad.	0.8 Watt cm^{-2}	$2 \times 10^{-3} \text{ eV} < E < 4 \times 10^{-2} \text{ eV}$

Table 3. Distribution of size and density of chunk deposits observed in 14.1 MeV neutron irradiation of Nb

Surface Conditions	Cold rolled, lightly chemically etched targets (Type A) ($\sim 5\mu\text{m}$ - $10\mu\text{m}$ microfinish)	Cold rolled, lightly electropolished targets (Type B) ($\sim 5\mu\text{m}$ microfinish)	Annealed for 2hrs at 1200°C in high vacuum, electropolished targets (Type C) ($\sim 2\mu\text{m}$ microfinish)	Annealed for 2hrs at 1200°C in high vacuum, electropolished targets (Type D) ($\sim 0.5\mu\text{m}$ microfinish)	Monocrystalline Nb (111) electropolished targets (Type E) ($\sim 0.5\mu\text{m}$ microfinish)
Total collector area investigated in cm^2	12	8	4	4	4
Neutron dose (n/cm^2)	5×10^{15} - 1.5×10^{16}	4.6×10^{15}	4.6×10^{15}	4.3×10^{15}	1.69×10^{15}
Ranges for chunk deposit density (no. of chunks per cm^2) [†]	5-25-(250*)	0-30-(1000*)	0-20-(100*)	0-10-(40*)	0
Ranges for average chunk diameters in μm	0.3-1 (Some cylindrical chunks up to $5\mu\text{m}$ long and $1.5\mu\text{m}$ dia)	0.3-5 (Cylindrical chunks up to $15\mu\text{m}$ long and $3\mu\text{m}$ dia)	0.3-1	0.05-1	—
Distribution of chunk size	45%: 0.3-0.5 μm 45%: 0.5-1.0 μm 10%: > 1 μm	35%: 0.3-1 μm 50%: 1-5 μm 15%: > 5 μm	100%: 0.3-1 μm	100%: 0.05-1 μm	—

[†] These are the smallest and largest number of chunks that can be found on a coherent surface area of 1cm^2 on the collector.

*These are the highest values observed in one particular run.

FIGURE CAPTIONS

- Fig. 1 Estimated needs for surface science data for U.S. fusion power development program: FTR (fusion test reactor), FERF (fusion engineering-research facility), EPRF (experimental power reactor I), EPRIT (experimental power reactor II), and DPR (demonstration power reactor) [taken from ref. 8].
- Fig. 2 SEMs of polycrystalline niobium surfaces irradiated at room temperature (a) with 100 keV $^4\text{He}^+$ ions to a total dose of 0.5 C/cm^2 , (b) an enlarged view of the blister skin in (a), (c) with 0.5 MeV $^4\text{He}^+$ ions to a dose of 1.0 C/cm^2 , (d) an enlarged view of blister skin in (c), (e) with 1.5 MeV $^4\text{He}^+$ ions to a dose of 1.0 C/cm^2 and (f) an enlarged view of the blister skin in (e). [taken from ref. 31]
- Fig. 3 (A) Scanning electron micrographs of blister skins in polycrystalline niobium irradiated at room temperature with $^4\text{He}^+$ ions with energies of (a) 100 keV, (b) 250 keV, (c) 500 keV, (d) 1000 keV and (e) 1500 keV, the total dose in (a) and (b) was 0.5 C/cm^2 and in (c), (d), and (e) was 1.0 C/cm^2 .
(B) Plots of projected range probability distributions (as shown by the dashed curves) as a function of depth into Nb target from the irradiated surface for different incident $^4\text{He}^+$ ion energies. The solid curves are plots of energy deposited into damage as a function of depth into the Nb target for $^4\text{He}^+$ ions with various projectile energies. The data points (a)-(e) are measured blister skin thickness values for the helium ion energies given in Fig. 2A. [taken from ref. 53]
- Fig. 4 Scanning electron micrographs of annealed polycrystalline vanadium surfaces after irradiation with 0.5-MeV $^4\text{He}^+$ ions to a total dose of 1.0 C/cm^2 : (a) at room temperature, (b) at $600 \pm 20^\circ\text{C}$, and (c) at $900 \pm 20^\circ\text{C}$. [taken from ref. 33]
- Fig. 5 (A) Erosion rates for annealed Type 304 stainless steel as a function of irradiation temperature for different projectile energies and total doses; $\bullet$: 0.5 C/cm^2 with 0.5 MeV $^4\text{He}^+$, $\square$: 0.1 C/cm^2 with 0.5 MeV $^4\text{He}^+$, $\circ$: 0.1 C/cm^2 with 100 keV $^4\text{He}^+$, Δ : 0.5 C/cm^2 with 100 keV $^4\text{He}^+$.
(B) Erosion rates for annealed polycrystalline vanadium as a function of irradiation temperature for 0.5 MeV $^4\text{He}^+$ ions and for a total dose of 1.0 C/cm^2 . The figures (a)-(d) at the top of fig. 4B show SEMs of irradiated surfaces for the temperatures indicated on the lower rate curve. [taken from ref. 31]
- Fig. 6 SEMs of surfaces of annealed Type 304 stainless steel after irradiation at 450°C with 0.5 MeV $^4\text{He}^+$ ions for total doses of (a) 0.1 C/cm^2 (b) 0.5 C/cm^2 and (c) 1.0 C/cm^2 . [taken from ref. 31]
- Fig. 7 SEMs of (111) Nb monocrystal surfaces after irradiation with 0.5 MeV He^+ to a total dose of 1.0 C/cm^2 , (a) at 900°C , He ions well channeled along the [111] axis, (b) at 700°C and for same channeling conditions as under (a), (c) at 20°C and for same channeling conditions as under (c), (d) at 900°C , He ions dechanneled. [taken from ref. 49]

FIGURE CAPTIONS, cont.

- Fig. 8 Niobium deposited on an aluminum substrate when a niobium target at ambient temperature (estimated to be near room temperature) was irradiated with 14 MeV neutrons to a total dose of 4.6×10^{15} neutrons/cm². (a) Scanning electron micrograph (backscattered electron images) of a niobium chunk deposited on an aluminum surface. (b) A x-ray energy spectrum of the niobium chunk in fig. 8a. (c) Nb L x-ray image of the same area as in fig. 8a. (d) Secondary ion ($^{93}\text{Nb}^+$) micrograph of the same area as in fig. 8a. Please note that the secondary ion micrograph was taken at much lower magnification than fig. 8a and fig. 8c. [taken from ref. 32]
- Fig. 9 Secondary ion ($^{93}\text{Nb}^+$) micrographs of niobium deposits on (a) an aluminum substrate, (b) a silicon substrate. Niobium released from cold rolled niobium target under 14 MeV neutron impact. [taken from ref. 32]
- Fig. 10 Scanning electron micrographs of surface of cold-rolled niobium after 14 MeV neutron irradiations to a total dose of 4.6×10^{15} neutrons/cm². [taken from ref. 32]

ESTIMATED NEEDS FOR SURFACE SCIENCE DATA

100 keV

500 keV

1.5 MeV

40 μm

200 μm

400 μm

2 μm

2 μm

2 μm

ANNEALED POLYCRYSTALLINE VANADIUM IRRADIATED
WITH 0.5-MeV $^4\text{He}^+$ TO A DOSE OF 1.0 C/cm^2

AT ROOM TEMP.

a 100 μm

AT 600° C

b 100 μm

AT 900° C

c 100 μm

200 μ m

200 μ m

200 μ m

900°C.

700°C.

20°C.

NIOBIUM DEPOSIT ON ALUMINUM
SUBSTRATE (NIOBIUM RELEASED BY
14-MeV NEUTRON IRRADIATIONS)

NIOBIUM DEPOSITS ON Al AND Si
SUBSTRATES (NIOBIUM RELEASED BY
14-MeV NEUTRON IRRADIATIONS)

40 μ m