A NEW APPROACH TO ASSESSING FUSION PLASMA-MATERIALS INTERACTIONS

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It is coming to be generally recognized that achievement of self-sustaining fusion reactions, particularly in tokamaks, may well depend significantly on the degree to which plasma-materials interactions can be controlled. Plasma radiations striking the surfaces of exposed components can cause (a) release of plasma contaminants that in turn can seriously affect plasma stability and attainment of fusion temperatures, and (b) damage and erosion of irradiated surfaces so as to limit the lifetime of irradiated components. The nature of the underlying processes and the extent to which they can affect the operation of future fusion reactors pose many unsolved questions. Researchers are attempting to find answers to these important questions by using the best tools currently available: accelerators, photon sources, and low-energy plasma devices. These facilities, however, have significant shortcomings in that a fusion reactor plasma will produce ions, neutral atoms, photons, electrons, and neutrons, while nearly all existing irradiation sources provide only one or two of these components at a time. Furthermore, all existing plasma devices are inadequate with respect to fluxes, fluences, and/or energies of most of the plasma radiation components expected in fusion reactors. In plasma devices and reactors, only integral surface effects characteristic of the plasma parameters and surfaces of those particular devices and reactors can be observed; integral surface effects result from the simultaneous interaction of radiation components with surfaces. Such integral effects cannot readily be extrapolated to plasma devices of different design and operating parameters.

Through the use of single-component irradiation facilities and low-energy plasma devices, a number of surface effects have been identified as contributing to potential plasma contamination and wall erosion problems. These effects include blistering, sputtering, chemical trapping and compound formation, gas desorption, gas reemission, vaporization, backscattering, photodecomposition, and photocatalysis. While single-component irradiations have provided some useful information concerning certain projectile/surface interactions, they cannot yield any information about synergistic or interactive effects. These effects arise from the simultaneous action of two or more separate components and together produce erosion and/or plasma contaminant release different from that expected from a simple summation of independent effects. It will therefore be necessary to determine the contributions to plasma contamination and to surface erosion arising from synergistic effects under multiple-component irradiation. Some examples of situations that are likely to give rise to synergistic phenomena are given below.

It has been shown that low-energy ion bombardment can produce gas-filled blisters that can rupture and exfoliate surfaces. Situations in which low-energy photons irradiate the skin of a blister produced by helium ion impact are highly likely in a fusion plant, and because of the reduced thermal contact with the bulk, the blister skin will be heated to a temperature above that of the substrate. This can be expected to reduce the yield strength in the skin, causing accelerated blister growth and rupture with an attendant enhanced gas release.

The simultaneous bombardment of a metal surface by energetic and chemically active deuterons and by energetic but chemically inert helium ions can be expected to result in concurrent chemical and physical trapping. The simultaneous formation of metal deuterides and helium blisters could lead to serious plasma contamination as well as erosion effects.

During the bombardment of a surface simultaneously by energetic neutrons, by reactive ions, and by photons, changes in the composition or in the chemical state of a surface are likely. Such changes could affect

1. erosion rates
2. the rates, composition, energy, and molecular state of plasma contaminants
3. the yield of secondary electrons
4. photon absorptivity and reflectivity of a surface
5. the surface electrical conductivity (particularly in the case of insulators)
6. the ion/neutral fraction of back-scattered particles
7. the work function
8. some mechanical properties, including surface hardness, stress rupture, and fatigue life of components (via crack initiation at surfaces).

Gas desorption has been shown to result from electron, ion, and photon bombardment of surfaces. Simultaneous particle and photon bombardments can be expected to alter the nature and charge distribution of the desorbed species. Furthermore, simultaneous bombardment of a surface by neutrons and ions could alter diffusion processes, e.g., by radiation-enhanced diffusion and by irradiation-induced segregation. In turn, desorption processes can be affected by altering the diffusion of species from the bulk to the surface. Finally, pronounced effects on gas-release rates, on the nature of the released species, and on surface photocatalysis and decomposition phenomena can be expected from the synergistic action of simultaneous photon, electron, and ion bombardment.

Further examples could be cited, but a comprehensive enumeration is not necessary to illustrate the range of possible synergistic effects. Suffice it to say that existing evidence suggests that many phenomena, especially those leading to (a) particle emission, (b) changes in surface physical and chemical properties, and (c) surface erosion, are worthy of examination in terms of synergistic effects.

It is very likely that information on synergistic effects and how to control their consequences may be required before first-generation reactors can be successfully operated. Furthermore, Tokamak Fusion Test Reactors (TFTRs) and/or Tokamak Experimental Power Reactors (TEPRs) may not provide the means of performing the requisite synergistic studies for full-scale fusion reactors. This is due to the fact that only integral effects can be measured and that the projected fluxes and energies of most of the plasma components are lower for TFTR and TEPR than those anticipated for a conceptual full-scale power reactor such as UWMAK-I (see Table I).

How then are the surface irradiation effects and plasma contamination studies that are needed to advance fusion power technology to be done? A detailed examination of this question by members of the Argonne National Laboratory Surface Science Center-Fusion Power Program shows that this could be done with an Advanced Multiple Component Radiation (AMCOR) (Fig. 1) facility, a facility that could be built using available technology. This facility would consist of accelerators, photon and ion sources, and analytical instruments, all integrated into a single facility. A target could be exposed simultaneously to fluxes of ions (D^+, T^+, $^4He^+$), electrons, photons (visible radiation, soft and hard x rays), and neutrons produced by the various radiation sources. The intensity and energy of each radiation component (see Table II) could be varied independently and could equal or exceed those anticipated in near-term (TFTR), in intermediate-term (TEPR), and, with the exception of the neutron component, in full-scale fusion power reactors. Also, *in situ* analyses could be done of both irradiation surfaces and emitted plasma contaminants. A facility such as AMCOR with its flexible combination of radiation components and analytical devices could be used to

TABLE I

Projected Fluxes and Energies of Particles and Photons Interacting with First Wall of Fusion (Tokmak) Reactors

	First Wall		
		Flux (cm^{-2} s^{-1})	$\underset{\sim}{E}_m$, Mean Energy or E, Energy Spectrum
UWMAK-I (Ref. 1) [500-MW(e) DT tokamak reactor]	D^+	6.4×10^{13}	23 keV
	T^+	6.4×10^{13}	23 keV
	$^4He^+$	4.7×10^{12}	23 keV
	$^4He^+$	1.7×10^{11}	~100 keV
	n	9.4×10^{13}	$E_m > 10^4$ keV
	n	3.4×10^{14}	$100 < E_m < 10^4$ keV
	Bremsstrahlung	Not cited in Ref. 1	Not cited in Ref. 1
TFTR[a] (Ref. 2)	$\left.\begin{matrix}D^+\\T^+\end{matrix}\right\}$ (total)	2.6×10^{16} cm^{-2} $pulse^{-1}$[b]	4-6 keV
	^4He (total)	3.6×10^{12} cm^{-2} $pulse^{-1}$[b]	~3.5 MeV
	n (fast)	3.6×10^{12} cm^{-2} $pulse^{-1}$[b]	14.1 MeV
	Bremsstrahlung	0.04 W/cm^2	Not cited in Ref. 2
TEPR-ANL (Ref. 4) 150 MW(th)	D^+	5×10^{14}	$\tilde{E} \sim 1$ keV Maxwellian distribution
	T^+	5×10^{14}	$\tilde{E} \sim 1$ keV Maxwellian distribution
	$^4He^+$ (fast)	7×10^{11}	$\bar{E} = 3.5$ MeV
	$^4He^+$ (slow)	1×10^{13}	$\tilde{E} = E_{\text{most probable}} \sim 1$ keV
	n (total)	3×10^{13}	$E \leq 14.1$ MeV
	n (fast)	0.8×10^{13}	$E = 14.1$ MeV
	Bremsstrahlung	1 W/cm^2	$E \sim 1$ keV

[a] The charge exchange neutral flux in the TFTR has been calculated to be ~10^{16} per cm^2 per pulse for D^0 energies in the range from 0 to 500 eV (see Ref. 3).

[b] Pulse length = 0.5 s (~1000 pulse/yr).

1. delineate synergism and study the underlying mechanisms
2. investigate plasma-wall interactions for various relevant materials and operating parameters
3. identify potential plasma contamination and/or surface erosion problems associated with different reactor designs
4. find and test potential solutions to significant contamination and erosion problems

An AMCOR-like facility therefore appears to be a useful and efficient complement to both single-source research tools and large-scale plasma test facilities. Moreover, such a facility could be built with existing technology and could be in operation in a time short enough to provide useful information even for the design and operation of near-term plasma devices.

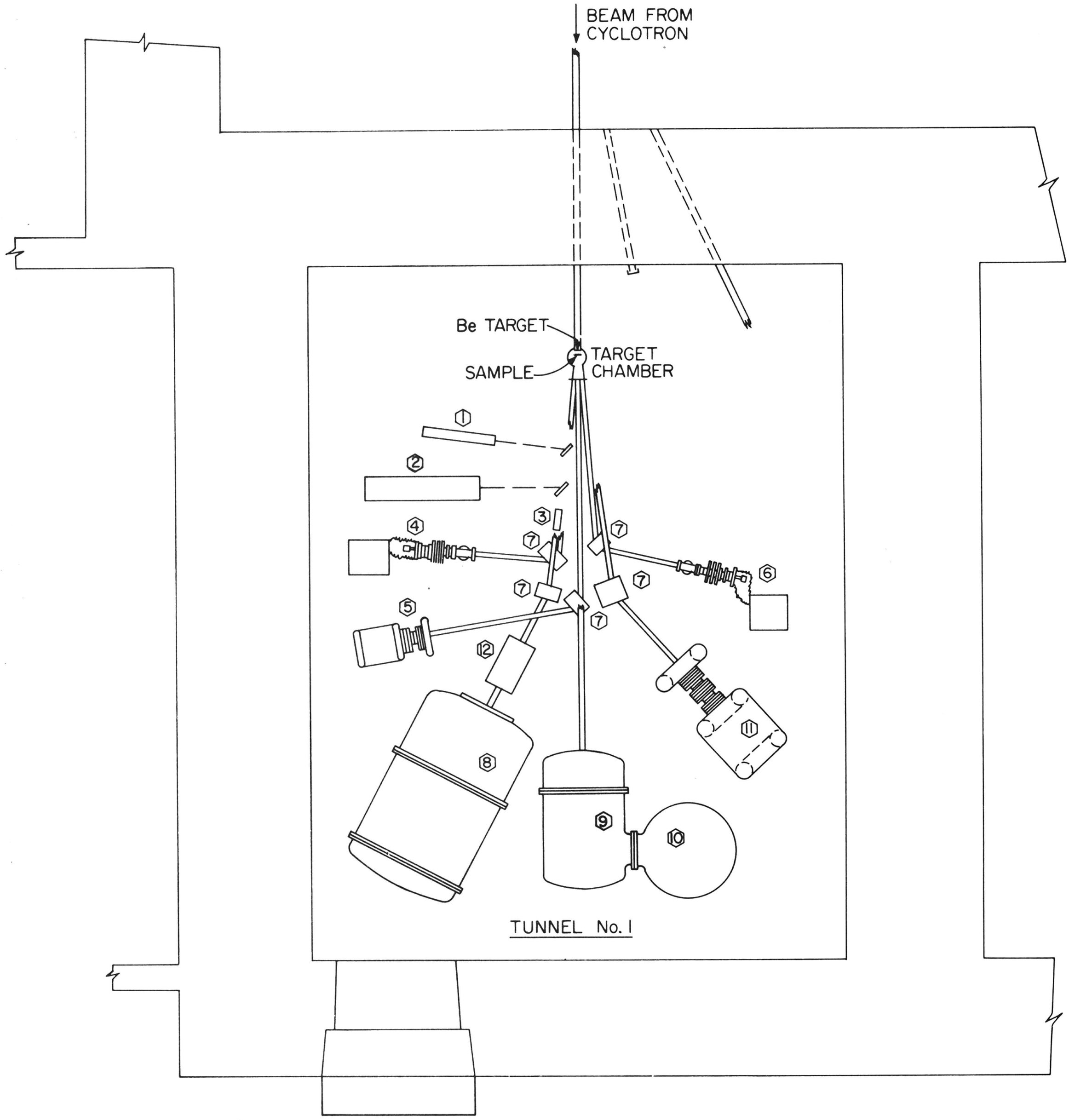

Fig. 1. A plan view of Tunnel No. 1 showing the location of principal items that comprise the AMCOR facility. Items 1, 2, and 3 are a CO_2 laser, an argon laser, and a Neodymium:YAG laser, respectively. Item 4 is a 25-kV deuterium source; item 5 is a 100-kV helium source; and item 6 is a 30-kV mass-three source. Item 8 is a 2-MV helium accelerator; items 9 and 10 are a 1-MV electron source and its power supply, and item 11 is a 300-kV deuteron accelerator. Items 7 are magnetic analyzers for the various accelerators, and item 12 is quadrupole doublet. Items 1, 9, and 10 are optional sources that can be added to complete the full complement of sources.

TABLE II

Source Type and Specifications for the Multiple-Component Radiation (AMCOR) Facility

Species	Energy Range	Flux on Target, $cm^{-2} s^{-1}$	Source Type
n	D-Be spectrum[a]	2×10^{12}	D-Be target
D^+	0-30 keV[b]	6×10^{11} to 1×10^{16}	Duoplasmatron
D^+	30-300 keV[b]	6×10^{11} to 1×10^{16}	Cockcroft-Walton electrostatic accelerator
$^3He^+$ (or T^+)	0-30 keV[b]	6×10^{11} to 1×10^{15}	Duoplasmatron
$^4He^+$	0-100 keV[b]	6×10^{11} to 6×10^{14}	Duoplasmatron
$^4He^+$ ($^4He^{++}$)	100 keV-2 MeV (3.5 MeV)[b]	6×10^{11} to 6×10^{13}	Electrostatic accelerator
e^-	0-30 keV[b]	6×10^{11} to 6×10^{13}	Electron gun
Photons	1.2 eV	10^{10} to 10^{16}	Neodymium:YAG laser
Photons	2 eV-1 keV	10^{10} to 10^{13}	Soft x-ray source
Photons	1 keV-30 keV[c]	10^{10} to 10^{13}	x-ray generator

[a] Typical for 22-MeV deuterons incident on a thick beryllium target. Neutron source is an optional component.

[b] Beam retardation and/or degradation techniques can be used to produce energy spectra that can be tailored to simulate desired distributions.

[c] The x-ray spectrum can be varied to a certain degree by choice of anode materials, electron acceleration voltage, and selective filters.

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