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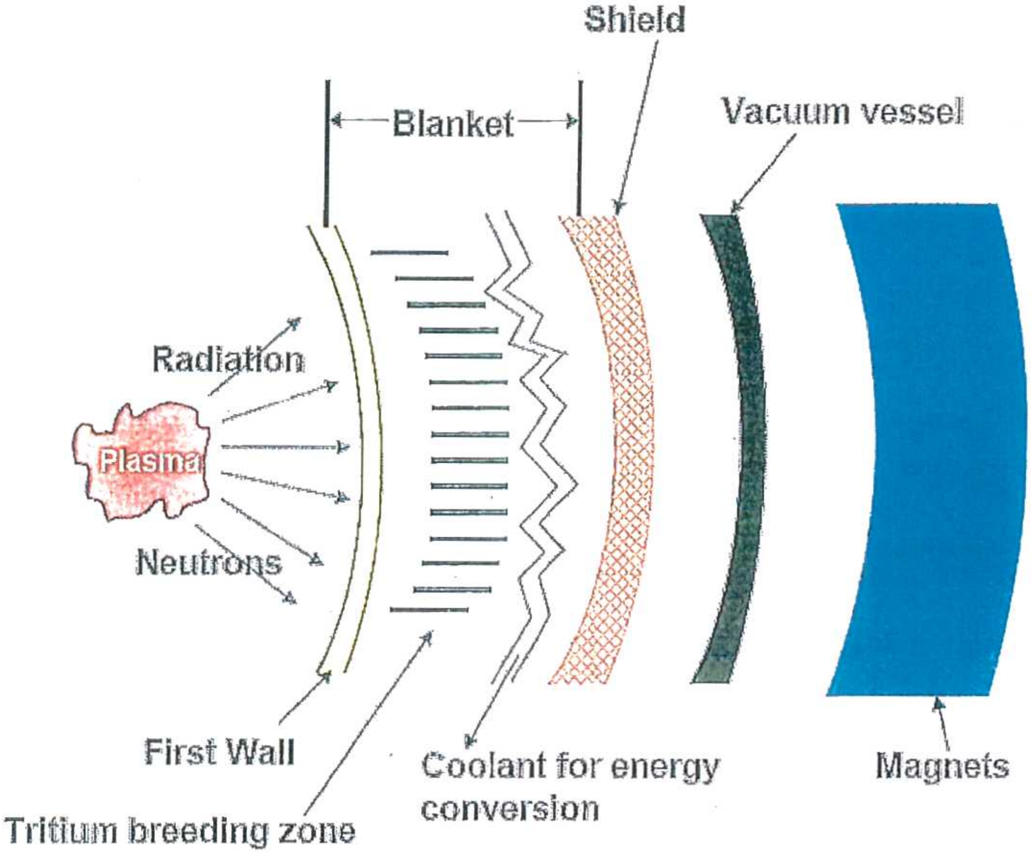


Figure 6.1 The main elements of the first wall, blanket, and shield. (Ihli 2008, Cismondi 2010)

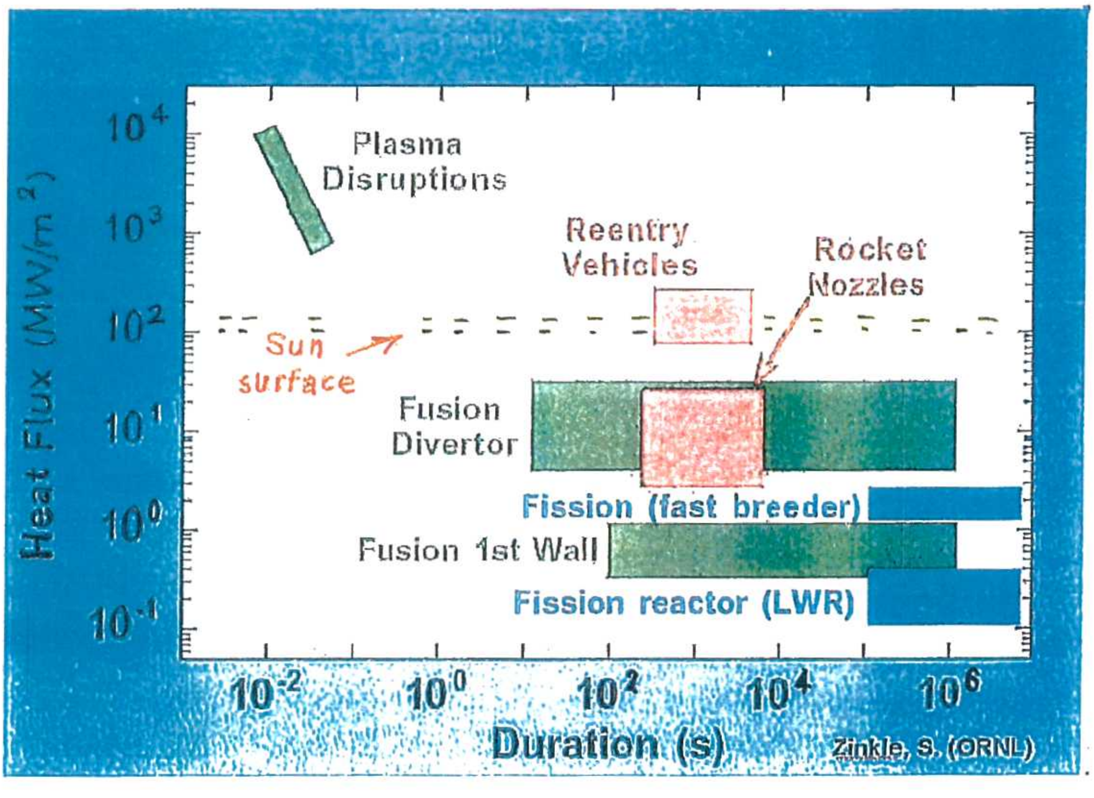


Figure 6.3 Comparison of ITER heat fluxes during normal operation and during disruptions with heat fluxes of other devices. (Ihli 2008, Norajitra 2010).

Dolan, ch. 8 MATERIALS ISSUES

A. Damage Analysis (§8.1/§8.2)

i) Fundamental :

- Note the typical neutron flux (or neutron current), Γ of the 14.1 MeV neutron energy (E) at a neutron wall loading, F_P of 1 MW/m^2 :

$$\Gamma = \frac{F_P}{E} = \frac{1 \times 10^6 \text{ Watt/m}^2}{14.1 \times 10^6 \times 1.6 \times 10^{-19} \text{ J}} = \underline{4.43 \times 10^{17} \text{ m}^{-2} \text{sec}^{-1}}$$

Typical total neutron flux $\simeq$ $\underline{3.6 \times 10^{18} \text{ m}^{-2} \text{sec}^{-1}}$.

These are subject to ~~the materials damage~~ studies :

Damage productions:

e.g. ⓐ (n, 2n) reaction ; Mn-55(n, 2n) Mn-54

⋮

ⓑ (n, p) reaction ; Fe-54(n, p) Mn-54 [$T_{1/2}$ = 303 days]

Ni-58(n, p) Co-58 [$T_{1/2}$ = 72 days]

⋮

ⓒ (n, γ) reaction ; Ni-58(n, γ) Ni-59* ~~$T_{1/2}$ = 8×10^4 y~~

$T_{1/2}$ = 5.3 y → Co-59 (n, γ) Co-60

= 45 d → Fe-58(n, γ) Fe-59

= 27.8 d → Cr-50(n, γ) Cr-51

= 92 d → Ni-62(n, γ) Ni-63

= 2.6 y → Fe-54 (n, γ) Fe-55

Mo-98(n, γ) Mo-99

Ta-181 (n, γ) Ta-182

Na-23 (n, γ) Na-24

⋮

These reactions grow w/ ~~neutron~~ energies & produce He + H gas atoms within the material → leads to "transmutation"

ⓓ (n, α) reaction ; Ni-59(n, α) Fe-56*

$T_{1/2}$ = 27.8 d → Fe-54(n, α) Cr-51

⋮

* transmutation reactions at thermal neutron energies.

e.g., production of primary (P) and secondary (S) knock-on atoms by an incident fast neutron (N)

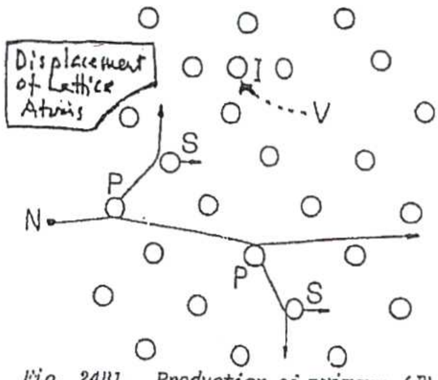
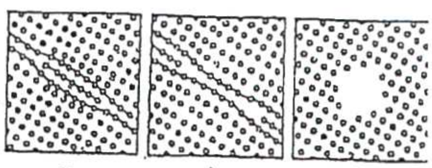


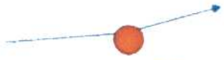
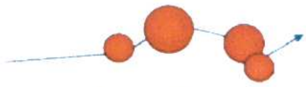
Fig. 24D1. Production of primary (P) and secondary (S) knock-on atoms by a incident fast neutron (N), resulting interstitials (I) and vacancies (V).

e.g. macroscopic "swelling"



a interstitial dislocation b vacancy dislocation c vacancy clusters

Table 8.1 Typical PKA energies from various types of irradiation (Rieth 2008)

Particle type (E_{kin} = 1 MeV)	Typical recoil (or PKA) feature	Typical recoil (PKA) energy T (eV)	Dominant defect type
Electron		25	Frenkel pairs (Vacancy and Insterstitial)
Proton		500	
Fe-ion		24,000	Cascades and sub-cascades
Neutron		45,000	

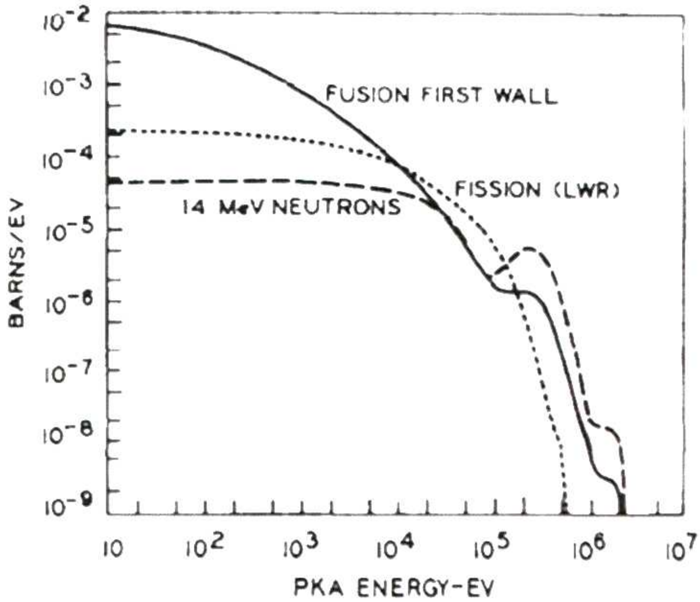


Fig. 8.5 PKA spectra for various neutron spectra incident on copper (Kulcinski 1976)

Table 8.2 Solid transmutation rates in fusion reactor materials for a neutron wall loading of 1 MW/m^2 (Kulcinski 1976)

Original metal	Transmutation product	Transmutation rate, appm/year
Al	Mg	400
	Si	40
SS 316	Mn	1,200
	V	200
	Ti	50
V	Cr	130
	Ti	80
Nb	Zr	700
Mo	Tc	400
	Ru	30

He + H production rates

measure of Radiation damage via → transmutations

→ displacement of lattice atoms by neutrons

(displacement threshold energy = 20-60 eV)

e.g.(*) SS-316 .... 40 eV

Al .... 25 eV

Nb .... 60 eV

(*) (see Table 24B1 of Dolan, F.R, Vol. III)

[Note: DPA (displacement atom):
If 1000 atomic displacements exist in a region w/ 10^6 atoms, then DPA = 10^{-3}.]

[Also: DPA/year is obtained using neutron spectrum(+):

e.g. SS-316 .... 10-12 dpa/yr

Al .... 10-15 "

Nb .... 7 "]

(+) example-I (Sesonske, P. 441): Nuclear Reactor Engg (1981)

A sample of steel (iron) is exposed to a fluence of 10^{24} neutrons/m^2, with an average energy of 0.1 MeV (thermal neutron); estimate the fraction of iron atoms that are displaced.

Note:
[neu. flux = # pcle/area·time
neu. fluence = # pcle/area
neu. intensity = # pcle/time]

$$\dot{n} = N\, \sigma_d(E)\ \phi(E),$$

Rate of prod^n of displacements by neutrons

atom density of target material

microscopic displacement X-section

flux of neutron of energy E

where $\sigma_d(E) \simeq \sigma_s(E)\,\dfrac{E}{A \cdot E_d}$,

$\sigma_s(E)$ = total elastic scattering X-section (m^2); target material for neutron en.

E_d = displacement threshold energy (eV)

A = mass number of target nucleus

E = neutron energy (eV)

$$\therefore \boxed{\dot{n} \simeq N\,\phi(E)\,\sigma_s(E)\cdot\frac{E}{A E_d}}$$

Hence, the total number of displaced atoms is equal to $\dot{n}(E)\,t$, and the fraction of displaced atoms is $n(E)/N$.

(cont'd)

(+) dpa example (cont'd):

Since the fraction of displaced atoms is $n(E)/N$, one has

$$\frac{n(E)}{N} \simeq [\underbrace{\phi(E)\cdot t}_{\substack{\text{fluence} \\ = \\ 10^{24}\ \text{neut}/m^2}}]\ \frac{\sigma_s(E)\ E}{A\cdot E_d}$$

, where $E = 0.1\ MeV = 10^5\ eV$
$A = 56$ for Fe
$E_d = 40\ eV$
$\sigma_s(E)\big|_{E=0.1\,MeV} \simeq 3\pi R^2$,
(with $R = 1.3\times10^{-15} A^{1/3}$ (m)
← radius of nucleus

$\therefore \sigma_s \doteq 3\pi\left[1.3\times10^{-15}\times(56)^{1/3}\right]^2$
$= 2.3\times10^{-28}\ m^2$

$$\therefore \boxed{\frac{n(E)}{N}} \approx \frac{(10^{24})(2.3\times10^{-28})(10^5)}{(56)(40)}$$

$$\boxed{= 0.010\ \text{dpa}}$$

[Note: If one uses [$\phi(E)$ value (flux)] instead, dpa/year will result.]

---

example-II (Prob. 6(a)):

Estimate dpa w/ known dpa/year: A SS-316 wall (annealed) undergoes a wall loading $P_n = 1.9\ MW/m^2$ (total flux $= 6.9\times10^{18}\ n/m^2\cdot s$) for 2 years. Estimate dpa.

From the context of the problem, one notes that this reaction is Fe-54 (n, p) Mn-54 solid $\boxed{\text{transmutation}}$.

From Table 24B3 for a neutron wall loading of $1\ MW/m^2$, for SS-316, the total Mn-54 production rate would be

$$\left(1200\ \frac{appm}{yr}\right)\times\left(\frac{1.9\ MW/m^2}{1.0\ MW/m^2}\right)\times(2\ \text{years}) = 4560\ appm\ !$$

[atom part per million]

- Combination of lattice damage (dpa) and gas production (appm of He) can produce "swelling" greater than expected for either phenomenon alone. → called "synergistic effect."

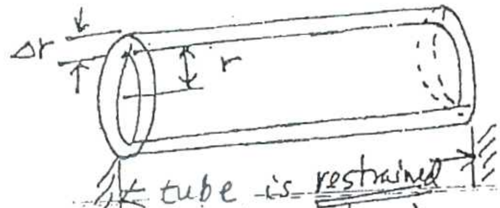
A. Damage Analysis – (Cont'd)

ii) Evaluations:

[Note: Desired properties of "first wall" are based on physical, electrical (resistant to arcing), chemical, neutronic, thermal, mechanical (strength, ductility), radiation environment, fabrication & supply considerations.]

Thermal stress:

long tube



ΔT between inner & outer walls. Thermal stress within the tube?

azimuthal & axial thermal stress components:

w/o proof;

$$\boxed{\begin{cases} \sigma_\theta(r) = \sigma_z(r) = \dfrac{-\alpha E \,\Delta T}{2(1-\nu)}\left(1+\dfrac{\Delta r}{3r}\right) \\[2ex] \sigma_\theta(r+\Delta r) = \sigma_z(r+\Delta r) = \dfrac{\alpha E\,\Delta T}{2(1-\nu)}\left(1-\dfrac{\Delta r}{3r}\right) \end{cases}} \quad \text{Eq (8.3)}$$

where α = thermal expansion coeff. ($^\circ K^{-1}$)
E = modulus of elasticity (Pa), Young's modulus
ν = Poisson ratio (0.25 – 0.35 for most metals

and $\Delta r \lesssim 0.2r$ (assumed).

[Note: If cylinder ends are not restrained, the stress in eq.(8.3) should be multiplied by 1.25 at $\Delta r = 0$.]

Heat flux,

$$\boxed{\frac{q}{A} = \frac{k\,\Delta T}{\Delta r}} \quad (\text{for } \Delta r \ll r), \ (W/m^2) \quad \cdots (8.4)$$

where $\begin{cases} q/A = \text{heat flux } (A = \text{wall area}) \\ r = \text{wall radius } (m) \\ k = \text{thermal conductivity } (W/m\cdot{}^\circ K) \\ \Delta r = \text{thickness} \end{cases}$

Poisson's ratio, ν(nu):

Assuming that the material is stretched or compressed along the axial direction (the x axis in the below diagram):

$$\nu = -\frac{d\varepsilon_{\mathrm{trans}}}{d\varepsilon_{\mathrm{axial}}} = -\frac{d\varepsilon_{\mathrm{y}}}{d\varepsilon_{\mathrm{x}}} = -\frac{d\varepsilon_{\mathrm{z}}}{d\varepsilon_{\mathrm{x}}}$$

where

ν is the resulting Poisson's ratio,
$\varepsilon_{\mathrm{trans}}$ is transverse strain (negative for axial tension (stretching), positive for axial compression)
$\varepsilon_{\mathrm{axial}}$ is axial strain (positive for axial tension, negative for axial compression).

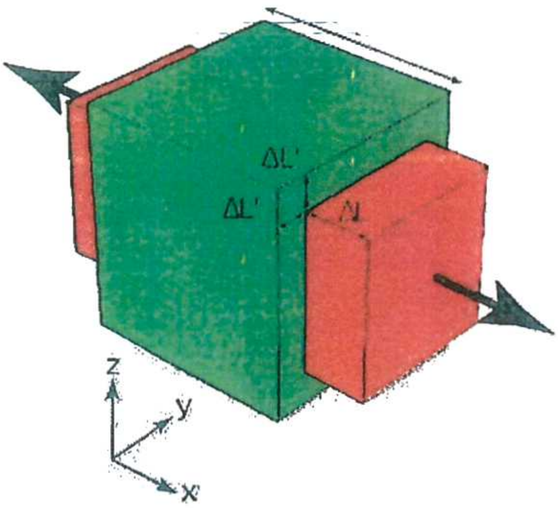


Figure 1: A cube with sides of length L of an isotropic linearly elastic material subject to tension along the x axis, with a Poisson's ratio of 0.5. The green cube is unstrained, the red is expanded in the x direction by ΔL due to tension, and contracted in the y and z directions by $\Delta L'$.

Poisson's ratio values for different materials

Material	Poisson's ratio
rubber	0.4999
gold	0.42 - 0.44
saturated clay	0.40–0.49
magnesium	0.35
titanium	0.34
copper	0.33
aluminium-alloy	0.32
clay	0.30–0.45
stainless steel	0.30–0.31
steel	0.27–0.30
cast iron	0.21–0.26
sand	0.20–0.45
concrete	0.20
glass	0.18–0.3
foam	0.10–0.40
cork	~ 0.00

Now, the average heat flux through a fusion reactor "first wall" can be written

$$\frac{q}{A} \simeq \frac{1}{\text{wall area}}\left[\text{heating power} + \text{fusion power} \ominus \text{neutron power}\right]$$

∵ little of neutron wall loading, P_n, appears as heat in the first wall

Recall: $Q \equiv \frac{P_{fusion}}{P_{input}}$.

Since $E_{neut} = 14.1$ MeV and $E_{fusion} = 3.5 + 14.1 = 17.6$ MeV for D-T reaction, $\frac{P_n \text{ (neutron wall loading)}}{P_{fusion}} \Rightarrow \frac{14.1}{17.6} \simeq 0.8011 \simeq \frac{4}{5}$.

$$\left(\frac{4}{5}\frac{1}{P_n}\right)^{-1}$$

Then, $\boxed{\frac{q}{A}} \simeq \frac{1}{A}\left(P_{in} + P_f - \frac{4}{5}P_f\right) = \frac{1}{A}\left(\frac{1}{Q} + \frac{1}{5}\right)P_f$

$$\boxed{= \frac{1}{A}\left(\frac{5}{4Q} + \frac{1}{4}\right)P_n}\left(\frac{W}{m^2}\right) \quad \cdots (8.6)$$

Example 8.1 :

Estimate the magnitude of the thermal stress in the wall of the following fusion reactor: toroidal

- neutron wall loading, $F_P = \frac{P_n}{A} = 2\ \frac{MW}{m^2}$,
- energy multiplication, $Q = 10$
- first wall thickness, $\Delta r = 0.5$ cm ($\Delta r \ll r$)
- thermal conductivity of SS, $k = 20$ W/m-°K
- & modulus of elasticity, $E = 1.8 \times 10^{11}$ Pa (Young's Modulus)
- thermal expansion coeff., $\alpha = 1.8 \times 10^{-5}$ °K^{-1}
- and Poisson ratio, $\nu = 0.3$ (typical for a metal)

[1 psi = 6894.76 Pa
1 atm = 1.013×10^5 Pa
= 14.7 psi]

From eq. (8.6), $\frac{q}{A} = \frac{P_n}{A}\left(\frac{5}{4Q} + \frac{1}{4}\right) = (2)\left(\frac{5}{4 \times 10} + \frac{1}{4}\right) = 0.75\ MW/m^2$;

& from eq. (8.4), $\frac{q}{A} = \frac{k}{\Delta r} \cdot \Delta T = \frac{20 \times 10^{-6}\ \frac{MW}{m \cdot K}}{0.5 \times 10^{-2}\ m}\Delta T$ ✓ $\therefore \Delta T = 188$ °K [78,851 psi]

Consider the toroidal reactor by a long cylinder w/ free ends;

Then, $\sigma_\theta(r) = \sigma_z(r) \cong (1.25) \cdot \alpha E \Delta T / 2(1-\nu) = (1.25) \times (1.8 \times 10^{-5})(188)(1.8 \times 10^{11}) / 2 \cdot (1-0.3) = 543.8 \times 10^6$ Pa

$r = \Delta r$

Ex. (Prob. 5)

Estimate the peak thermal stress in a 5 mm vanadium wall with a linear expansion coeff. of $7.9 \times 10^{-6}\ °K^{-1}$, a modulus of elasticity of 1.3×10^{11} Pa, Poisson's ratio of 0.3 and the toroidal reactor specifications of $Q = 12$ and $P_n = 2.2\ MW/m^2$ (max.) Wall temperature is ~ 1000 °K.

ans: The thermal stress in the wall can be estimated using eq. (8.3) approximating the torus as a long cylinder with free ends (for which the maximum thermal stress is 1.25 times the stress given in the equation w/ $\Delta r = 0$):

$$\sigma_\theta = \frac{(1.25)\,\alpha E \Delta T}{2\cdot(1-\nu)},\quad \left\{\begin{array}{l} \alpha = \text{thermal expansion coeff} \\ \quad = 7.9\times10^{-6}\ °K^{-1} \\ E = \text{modulus of elasticity} \\ \quad = 1.3\times10^{11}\ Pa \\ \nu = \text{Poisson's ratio} \\ \quad = 0.3 \end{array}\right.$$

Now, ΔT = temperature difference across the wall (°K) can be obtained using

eq. (8.4), $\frac{q}{A} = k\,\Delta T/\Delta r$

From (8.6), $\frac{P_n}{A}\left(\frac{1}{4}+\frac{5}{4Q}\right)$

$= (2.2\times10^{6})\left(\frac{1}{4}+\frac{5}{4\times12}\right)$

$= 7.79\times10^{5}\ (W/m^2)$

$\Rightarrow \Delta T = \left(\frac{q}{A}\right)\left(\frac{\Delta r}{k}\right)$

$= (7.79\times10^{5}) \times \left(\frac{5\times10^{-3}\ m}{38.6}\right)$

$= \underline{100.91\ °K}$

Note: k = thermal conductivity of Vanadium at 1000 °K $= 38.6\ \left(\frac{W}{m\ °K}\right)$ [Table 8.10]

$$\therefore \sigma_\theta = \frac{(1.25)\cdot(7.9\times10^{-6})(1.3\times10^{11})(100.91)}{2\cdot(1-0.3)} = 9.25\times10^{7}\ Pa$$

[or $\sigma_\theta = (9.25\times10^{7}\ \cancel{Pa})\times 1.45\times10^{-4}\ \left(\frac{psi}{\cancel{Pa}}\right) = \underline{\underline{1.34\times10^{4}\ psi}}$]

To minimize the thermal stress, σ:

$\boxed{\begin{array}{l}\text{need } \Delta r\downarrow \\ (\text{hence, } \Delta T\downarrow)\end{array}}$ $\left[\because \underbrace{\frac{q}{A}}_{\substack{\text{with fixed heat flux} \\ \text{(i.e., wall loading)}}} = \frac{k}{\Delta r}\Delta T \rightarrow \text{ as } \Delta r\downarrow, \Delta T\downarrow \text{ w/ fixed } \frac{q}{A}\right]$

$\uparrow$

[by using materials with lower $\frac{\alpha E}{k(1-\nu)}$

(since $\Delta T \sim \frac{1}{k}$ w/ fixed $\left(\frac{q}{A}\right)$ + Δr)]

Recall:

Eq. (8.3) $\rightarrow$ $\sigma_\theta(r+\Delta r) = \sigma_z(r+\Delta r)\Big|_{\Delta r \ll r} \simeq \frac{\alpha E(\Delta T)}{2(1-\nu)}$

Eq. (8.4) $\rightarrow$ $\frac{q}{A} = k\frac{\Delta T}{\Delta r}$

$\Big\} \rightarrow \left[\frac{q}{A} = \left(\frac{k}{\Delta r}\right)\cdot\left(\frac{2(1-\nu)\,\sigma_\theta}{\alpha E}\right)\right]^{-1}\sigma_y$

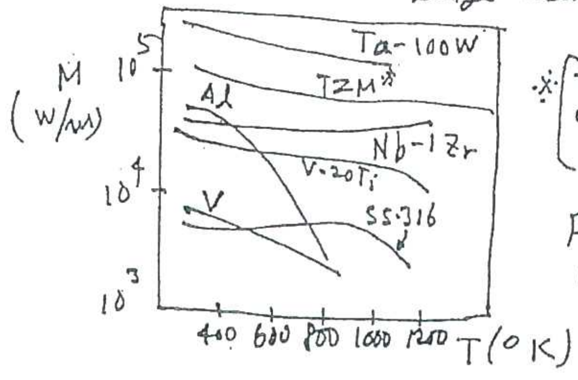
$\therefore$ Ratio of yield stress to thermal stress: (while keeping $\sigma_\theta \simeq \sigma_z < \sigma_y$) $\Rightarrow \left(\frac{\sigma_y}{\sigma_z}\right) = \left(\frac{\sigma_y}{\sigma_\theta}\right) = \frac{\overbrace{k\cdot 2(1-\nu)\cdot\sigma_y}}{(q/A)\cdot\Delta r\cdot\alpha E}$ $\;\;\frac{k\cdot 2(1-\nu)\cdot\sigma_y}{\alpha E} \equiv M$

$\therefore \boxed{\frac{\sigma_y}{\sigma_z} = \frac{\sigma_y}{\sigma_\theta} = \frac{M}{\left(\frac{q}{A}\right)\cdot\Delta r}}$

[cf. $M \equiv \frac{2(1-\nu)\,\sigma_y\cdot k}{\alpha E}$ (W/m)

= thermal stress parameter]

$\uparrow$ larger the better to permit large heat fluxes



※[TZM is an alloy of Mo with 0.5% Ti, 0.08% Zr and 0.03% C.]

Fig. 8.6
UWMAK III Report
p. 9-24

B. Mechanical Behavior (separate lecture)

C. <u>Plasma Materials Interactions</u>

i) <u>Hydrogen Recycling</u> (§8.5)

- Hydrogen : all isotopes of D, T, and H.
- recycling : process where hydrogen gas atoms from the wall penetrate to the plasma.

a) reflection (or backscattering) – incident atom or ion re-emerges from the wall during its interact$^{=}$ w/ wall atoms

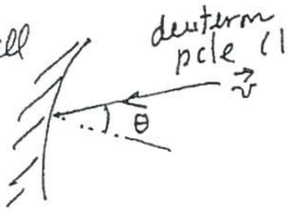
reflection coeff. can be written in terms of <u>Linhard reduced energy</u>,

$$\boxed{\varepsilon = \frac{32.5\, m_2 W_1}{(m_1+m_2) Z_1 Z_2 (\sqrt{Z_1}+\sqrt{Z_2})^{2/3}}}, \quad \text{(dimensionless)} \cdots (8.11)$$

where
- m_1, m_2 = incident pcle, target atom masses
- Z_1, Z_2 = 〃 nuclear charge, target nucl. ch. numbers
- W_1 = monoenergetic incident pcle energy (keV) or Maxwellian temperature

<u>ex</u> :

Al wall



θ=0 : normal incidence

Fraction of deuterons which are <u>trapped</u> in the surface.

<u>ans</u>. Reflection coeff. $r_n \equiv \dfrac{\#\text{ of reflected pcles}}{\text{incident pcles}}$

$$\boxed{r_n \simeq 0.35 - 0.2 \log_{10} \varepsilon} \quad (0.01 < \varepsilon < 10) \cdots (8.12)$$

Note; m_1 = deuteron = 2

m_2 = aluminum = 27

Z_1 = 1

Z_2 = 13

and W_1 = 1 <u>keV</u>

now, from eq. (8.11), $\varepsilon = \dfrac{(32.5)(27)(1)}{(2+27)(1\times 13)(\sqrt{1}+\sqrt{13})^{2/3}} \simeq 0.84$

From eq. (8.12), refl$^{=}$ coeff, $r_n = 0.35 - 0.2 \log_{10}(0.84) \simeq \underline{0.36}$

∴ The fraction trapped is $(1-r_n) = \underline{0.64}$!

i) Hydrogen Recycling (cont'd):

b) spontaneous desorption (or thermal desorption) — <u>departure</u> of <u>adsorbed</u> hydrogen atoms on the wall surface. This phenomenon occurs via molecular <u>recombination</u> on the surface.

$$\boxed{(\text{Spontaneous desorption flux}) = K\, c^2(x=0,\ t=t)} \quad \left(\frac{\text{atoms}}{m^2\cdot \text{sec}}\right)$$

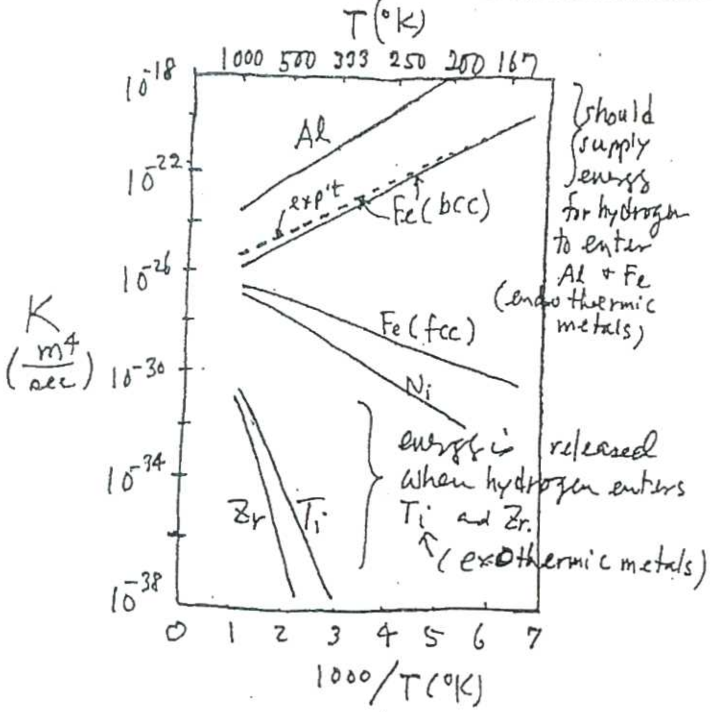
distance from the surface to hydrogen concentrat$^{\underline{n}}$

time

Note: $c(x,t)$ = hydrogen atom concentration (atoms/m^3)

$$\boxed{\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left[D\frac{\partial c}{\partial x}\right] + S(x,t)}$$: Diffusion eq.

K: recombination rate parameter (surface effect), (m^4/sec)



c) stimulated desorption (or gas sputtering) — ejection of <u>adsorbed</u> atoms <u>on</u> the wall surface (or <u>absorbed near</u> the wall surface) by incident ions, atoms, e's, or photons

Much more effective than "spontaneous desorption" for the multilayers of adsorbed gas on the wall

$$\boxed{(\text{Stimulated desorption flux}) = \begin{cases} A\,\Gamma_i\, c(0,t) & (\text{gas sputtering}) \\ A_1\,\Gamma_i \left(\frac{\partial c}{\partial x}\right)_{x=0} & (\text{accelerated diffusion}) \end{cases}}$$

where Γ_i = incident ion flux

A, A_1 = constants $[\ \underline{A \sim \sigma_d \lambda / 4}\ ]$, σ_d = desorption x-sect$^{\underline{n}}$

λ = mean free path of incident ion

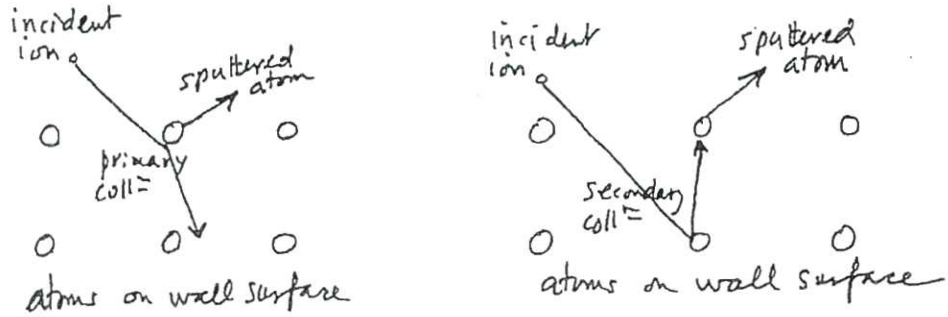
($\sigma_d \sim 10^{-19}$–10^{-20} m^2) for H^+ + Ar^+ ions on adsorbed gases

For monolayers, this corresponds to <u>0.5–10 atoms/ion</u>

C. Plasma Materials Interactions

ii) Impurity Introduction (§8.6)

a) physical sputtering – average number of wall atoms ejected per incident ion (Sputtering yield, S)



sputtering yield for light ions at normal incidence,

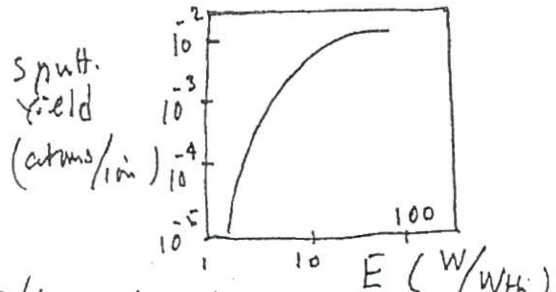
$$\boxed{S = 0.0064\, m_2\, \gamma^{5/3}\, E^{1/4} \left(1 - \frac{1}{E}\right)^{7/2},} \quad \text{for } 1 < E \lesssim 30 \;\; \& \;\; \frac{m_1}{m_2} \leq 0.4$$

where m_1, m_2 = incident ion and wall atom masses

$$\gamma \equiv \frac{4\, m_1 m_2}{(m_1 + m_2)^2}$$

$$E \equiv \frac{W \text{ (incident ion en.)}}{W_{th} \text{ (threshold energy)}}, \quad W_{th} = \frac{W_B \text{ (surface binding en. of wall atoms)}}{\gamma(1-\gamma)}$$

normalized ion energy



• wall surface erosion rate (by sputtering);

$$\boxed{\frac{dx}{dt} = \frac{1}{n_w} \sum_j \phi_j S_j} \quad (m/sec) \;\; ..(8.22) \;\& \left[\text{cf. Ex. 8.3 \& prob. 2}\right]$$

where n_w (density of wall atoms) $= \frac{\rho N_A N_a}{M}$

ϕ_j = flux of ions (pcles/m²·sec)

S_j = sputtering yield

j = ion species

ρ = target mass density
N_A = Avogadro's #
N_a = # of target atoms per target molecule = 2 for H in H_2O
M = molecular weight of target (kg/mole)

ii) Impurity (cont'd)

b) physichemical sputtering — sputtering where both K.E. and chemical binding en. affect sputt. yield

c) chemical erosion (or chemical sputtering) — chemical effects on sputtering;

(e.g. $\underbrace{H \rightarrow \text{graphite}}$ → produce hydrocarbon (like methane, acetylene)

d) desorption — introduction of surface impurities like C, N, H_2O, and O from the chamber walls.

Plasma discharge (baking out the vacuum chamber helps to remove most of impurities on the walls)

(adsorbed monolayers)

Recall and note:

(Stimulated desorption by ions) > (Stimulated desorpt^n by electrons) > (Stimul. desorp^n by photons)

(~ 0.5-10 atoms/ion) (~ 0.01 - 0.1 molecules/electron at 0.1-0.5 keV of E_e.) (~10^{-3} molecules/photon)

e) vaporization — atoms removed from the surface of a metal under vapor pressure

vapor pressure;

$$\boxed{p = P_0 \, e^{-\Delta H/T}} \text{ (Pa)}$$

where ΔH = energy required to remove an atom from the metal surface

$\simeq$ 5 - 10 eV

P_0 = constant

T = temp (in eV)

surface evaporat^n flux;

$$\boxed{\varphi_n = 2.6 \times 10^{24} \frac{\alpha p}{\sqrt{AT}}} \left(\frac{\text{atoms}}{\text{m}^2 \cdot \text{sec}}\right) \text{ (24G7)}$$

where $\alpha \simeq 1$ (sticking coeff.)

A = atomic weight (g/mole), T in °K, p (vapor press.) in Pa.

e) vaporization (cont'd) —

wall erosion rate ;

$$\boxed{\frac{dx}{dt} = \frac{\phi_m}{n_w}} \quad (m/sec) \cdots (8.25)$$

[cf. Example 8.4]

also; Ex (Prob. 8.3): Estimate the evaporation rate (mm/yr) for T_i wall at 1400°K (constant wall temperature).

ans. The evaporation rate can be determined from eq. (8.25)

$$\boxed{\frac{dx}{dt} = \frac{\phi_m}{n_w}}$$, where n_w = wall atom density

For constant wall temperature.

$\Rightarrow \rho \, N_A \, Na / M$ (atoms/m³)

ρ = target mass density of Ti = 4.51 gm/cm³ = 4510 kg/m³

$N_A = 6.022 \times 10^{23}$ molecules/mole

N_a = # of target atoms per target molecule = 1

M = molecular weight of target = 0.047 kg/mole

$$\therefore n_w = \frac{(4510)(6.022 \times 10^{23}) \cdot 1}{(0.047)} = 5.78 \times 10^{28} \left(\frac{atom}{m^3}\right)$$

ϕ_m = surface evaporation flux (Eq. 8.24),

$$= 2.6 \times 10^{24} \frac{\alpha p}{\sqrt{AT}}$$

with $\alpha \equiv$ sticking coeff $\simeq 1$

p = equilibrium vapor pressure of Ti = 2×10^{-5} Pa (at 1400°K) < From Fig. 8.25 >

A = atomic weight = 47.9 gm/mole

T = 1400°K

$$= \frac{(2.6 \times 10^{24})(1)(2 \times 10^{-5})}{[(47.9)(1400)]^{1/2}}$$

$$\Rightarrow \phi_m = 2.01 \times 10^{17} \left(\frac{atoms}{m^2 \cdot sec}\right)$$

$$\therefore \boxed{\frac{dx}{dt}} = \frac{2.01 \times 10^{17} \left(\frac{atoms}{m^2 \cdot sec}\right)}{5.78 \times 10^{28} \left(\frac{atoms}{m^3}\right)} = 3.48 \times 10^{-12} \left(\frac{m}{sec}\right) \times \left(\frac{10^3 \, mm}{1 \, m}\right) \times \left(\frac{3.1536 \times 10^7 \, sec}{1 \, yr}\right)$$

$$= \underline{\underline{0.11 \text{ mm/yr}}}$$

For <u>varying</u> temperature on the wall;

Temp. rise ΔT;

$$\boxed{\Delta T = \frac{2W}{S\sqrt{\pi c_p k \rho_m \tau}}} \quad ({}^\circ K)$$

where
- $W(J)$ = total energy (J)
- S = wall surface area (m^2)
- τ = time interval while total en. is dumped on surface area
- c_p = specific heat ($J/Kg \cdot {}^\circ K$)
- k = thermal conductivity ($\frac{W}{m\,{}^\circ K}$)
- ρ_m = density (Kg/m^3)

[cf. prob. 8.4]

Then, the number of wall atoms evaporated by pulse in τ is

$$\boxed{\frac{\Delta n}{S} \simeq 0.1\ \tau\, \phi_n(T_{max})}, \quad \left(\frac{atoms}{m^2}\right)$$ [cf. prob. 8.4]

where $\phi_n(T_{max})$ = evaporation rate at peak temp.

[En. dumps (evenly distributed on the wall) at $\tau > 0.1$ sec for tokamak reactor of <u>not</u> concern.]

f) blistering and flaking – e.g. penetration of energetic He-ions into wall.

critical pressure for blister formation,

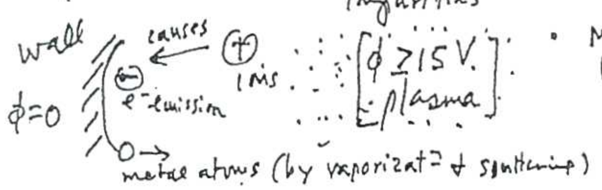
$$\boxed{P_{cr} = \frac{4\sigma_y t^2}{3r^2}} \quad \cdots (8.29)$$

- σ_y = metal yield strength
- t = blister skin thickness
- r = bubble size

[Note: At given incident ion energy, r and t are insensitive to wall temperature

but <u>$\sigma_y \downarrow$ with $T\uparrow$</u>]

g) unipolar arc – arcs bet^n plasma + walls / limiter create impurities



- Most of current is carried out by electrons.

h) synergistic effects – non linear effects of superposition of various individual processes
[e.g. physical, chemical $\}\rightarrow$ physichemical process]

C. Plasma Material Int'ns (cont'd)

iii) Near-Surface Wall Modifications

- phase changes
- alloy composition changes
- micro structural "
- macro " "
- property changes
- materials development

D. Special purpose Materials

- graphite + silicon carbide
- heat-sink materials
- ceramics
- superconducting magnet materials