15.9 Sweeping of Gas Bubbles by grain Boundaries

Object is to find when the velocity of the GB = velocity of a bubble dragged by a GB

(15.199)

$$v_b = \left[\frac{3a_o^4 D_{os}}{4R_{gb}^3}\right]\left(\frac{2\gamma_{gb}}{kT}\right)\sin(2\phi)\bullet\exp\left(-\frac{E_s}{kT}\right)$$

(15.205)

$$v_{gb} = \left\{\frac{\nu a_o^4}{R_c}\right\}\left(\frac{2\gamma_{gb}}{kT}\right)\left[1-\left(\frac{R_{gb}}{{}_{gb}}\right)^2\left(\frac{R_c}{2R_{gb}}\right)\sin(2\phi)\right]$$

normally $\sin(2\phi) < 1$

if it is,bubble is too big and GB passes it by

(Figure 15.25) K(R_c, T)

Radius of Curvature

Main point is that small bubbles are swept up on GB's and as they grow, they eventually get left behind

See Figure 15.26

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15.10 Gas Release Models Based on Bubble Migration *Read but not of much use.*

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15.11 Engineering Fission Gas Release Calculations

So far, no theory is adequate to accurately predict gas release

** Rely on empirical relations*

Important : Find that fission gas release can be correlated with power changes, i.e., startup, shutdown, ==> implies that fuel cracking is very important and there is no very good way to model that !

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Study Figure 15.29

$$\bar{f} = \left(\frac{1}{\pi R^2}\right)\int f(T)\,2\pi r\,dr$$

One can also convert so that f is a function of linear power level

See figure 15.30

The way to use this is to find out average f at a given value of , and then sum up axially for various values of .

Gas released per

unit length of fuel $= Y_{Xe}\left(\dot{F}t\right)_1 \pi R^2 \bar{f}(\ \ _1)$

- -

Igore the rest of the section

Problem 15.2

let $\overset{\circ}{\mu}_g$ = range of
FF in gas $\approx$ 2 cm
(1 atm.)

- **assume FF energy decreases linearly with fraction of range covered**

- **Energy of FF when it travels distance r in fuel pellet**

$$E_s = E_o\left[1-\left(\frac{r}{\mu_{ff}}\right)\right] \quad \text{where } E_0 = \text{birth energy}$$

Calculate, f_{rec}^{Esc} the fraction of escaping fission fragment recoils stopped in the fuel - cladding gap.

$$t_g = 0.008 \text{ cm}$$

$\eta = \cos\theta$
$dV = 2\pi r^2\,dr\,d\eta$
(hemispherical ring
or spherical shell)

Consider a FF emerging from the surface at an

angle $\cos^{-1}\eta$ after transversing a distance r of fuel.

a.) distance through the gas = = $\frac{t_g}{\eta}$

b.) Energy after passage through the gas in the gap = E

$$E = E_s \left(1 - \frac{t_g}{\eta \mu_g}\right)$$

$$E = E_s \left(1 - \frac{t_g E_o}{\eta \mu^{\circ}_g E_s}\right)$$

If E = 0 when FF particle reaches the clad;

$$1 - \left(\frac{t_g E_o}{\eta \mu^{\circ}_g E_s}\right) = 0$$

or, energy of particles that just stay in the gas

$$E_s = \frac{t_g E_o}{\eta \mu^{\circ}_g} = E_o \left(1 - \frac{r}{\mu_{ff}}\right)$$

or,

$$\left(1 - \frac{r}{\mu_{ff}}\right) = \frac{t_g}{\eta \mu^{\circ}_g} \qquad (1)$$

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at a given polar angle ($\cos^{-1}\eta$), all FF's created

at r, where $r_m <$ $r < \mu_{ff}$ will be stopped in gas, where r_m is defined by eq. 1. (if r< r_m, FF will end up in cladding)

$$\frac{r_m}{\mu_{ff}} = 1 - \frac{t_g}{\eta \overset{\circ}{\mu}_g}$$

$$\text{so} \quad 0 < \frac{r_m}{\mu_{ff}} < 1 \quad \text{or } \eta > \frac{t_g}{\overset{\circ}{\mu}_g}$$

Now $Y\dot{F}$ **= source strength of FF's, $cm^{-3}s^{-1}$**

FF current at surface of fuel due to generation in volume dV

$$dj = \frac{Y\dot{F}dV}{4\pi}\left(\frac{\eta}{r^2}\right)$$

$$= \frac{Y\dot{F}}{2}\left(dr\,d\eta \bullet \eta\right)$$

Let j' = current at the surface which will stop in the gas.

$$j' = \frac{Y\dot{F}}{2}\int_{0}^{1}\eta\, d\eta \left[\int_{r_m}^{\mu_{ff}} dr\right]$$

$$j' = \frac{Y\dot{F}}{2}\int_{0}^{1}\eta\, d\eta\left[\mu_{ff} - r_m(\eta)\right]$$

$$= \frac{\mu_{ff} Y\dot{F}}{4}\left[1 - 2\int_{0}^{1}\left(\frac{r_m(\eta)}{\mu_{ff}}\right)\eta\, d\eta\right]$$

for η ***integration;*** $\eta > \frac{t_g}{\mu_g^o}$ ***use above formula***

$\eta < \frac{t_g}{\mu_g^o}$ $r_m = 0$

therefore

$$2\int_{0}^{1}\frac{r_m(\eta)}{\mu_{ff}}\eta\, d\eta = 2\int_{\frac{t_g}{\mu_g^\circ}}^{1}\left(1 - \frac{t_g}{\eta\mu_g^\circ}\right)\eta\, d\eta$$

$$= \left(1 - \frac{t_g}{\mu_g^\circ}\right)^2$$

And furthermore,

$$j' = \frac{\mu_{ff} Y \dot{F}}{4}\left[1 - \left(1 - \frac{t_g}{\mu^{\circ}_g}\right)^2\right]$$

By comparison with recoil formula;

$$I^{rec} = \frac{\mu_{ff} Y \dot{F}}{4}$$

or,

$$\eta_{rec} = \frac{j'}{I^{rec}} = 1 - \left(1 - \frac{t_g}{\mu^{\circ}_g}\right)^2$$

for $\frac{t_g}{\mu^{\circ}_g} < 1$

$$\eta_{rec} = 2\,\frac{t_g}{\mu^{\circ}_g}$$

==================================

with $t_g = 0.008$ **cm ,** $\mu^{\circ}_g = 2$ **cm**

$$\eta_{rec} = 2 \bullet 8 \times 10^{-3}/2 = 0.008$$

0.8% of FF’s stop in gas

Observations on Corrosion

- **Current Failure Mechanisms**

  1.) BWR's-CILC
  2.) PWR's-Mechanical fretting/manufacturing defects

- **Corrosion of Zircaloy**

  1.) Oxide Buildup===> Heat Transfer
  2.) Metal Thinning===>Mechanical Degradation

BWR's

- **@ 300°C and 1000 psig high purity water w/o irradiation**

  Black oxide-thickens uniformly @ 2-3 microns/y

- **Same conditions as above in-reactor**

  Whitish nodular corrosion (local breakdown of protective ZrO_2)
  Much higher growth rate- 70-120 microns/30 GWd/MT

- **Nodular corrosion itself has never resulted in fuel performance problems**

- **Problems occur when CILC appears**

  In early 70's found Cu oxide sandwiched between ZrO_2 layers
  the Cu oxides appear to physically damage ZrO_2 layers

- **Ingredients for CILC failure**

  Corrosion susceptibility of Zircaloy
  Availability of Cu (and other elements) in solution

- **Many Utilities have replaced Cu based condensers with SS**

PWR's

- Operating conditions enhance uniform corrosion rate

    Water T ≈ 30°C higher
    Pressure ≈ 500 psig higher
    Addition of LiOH and boric acid
    Hydrogen over pressure to maintain water in reducing state

- Nodular corrosion rarely reported in PWR's

    Absence of boiling
    Low oxygen content
    Uniform layer spalls to eventually form less protective whitish uniform oxide
    In general oxide layer increases with increasing T

- Fuel rod corrosion performance under normal conditions satisfactory

    Up to 40-50 GWd/MT (50-75 microns)
    Corrosion and Hydriding may become limiting > 50 GWd/MT
    Move to Zirlo alloy discussed previously

Fixes for Corrosion

- Generally, reduce nodular corrosion by reducing the size of the precipitates (increase solute concentration)

- Generally, reduce uniform corrosion by increasing the size of the precipitates (reduce solute concentration)