Chapter 15
Fission Gas Release

Once gas is released;

- **it does not diffuse back into the solid**
- **it does not slow the diffusion out of the solid**
- **the gas pressure can cause sintering**

T< 1300 °K	***gas atoms "frozen"***
1300<T<1900 °K	***diffusion release***
1900<T ° K	***bubble release***

15.2 Experimental Techniques - Read

15.3 Recoil & Knockout

figure 15.7, Table 15.1

P_i ≡ rate of generation of recoils of species i per unit volume at a distance x from the surface.

q_i ≡ rate at which particles of species i are stopped in a unit volume of solid at a distance x from the surface.

I_i ≡ rate at which recoil of species i cross a unit area of surface.

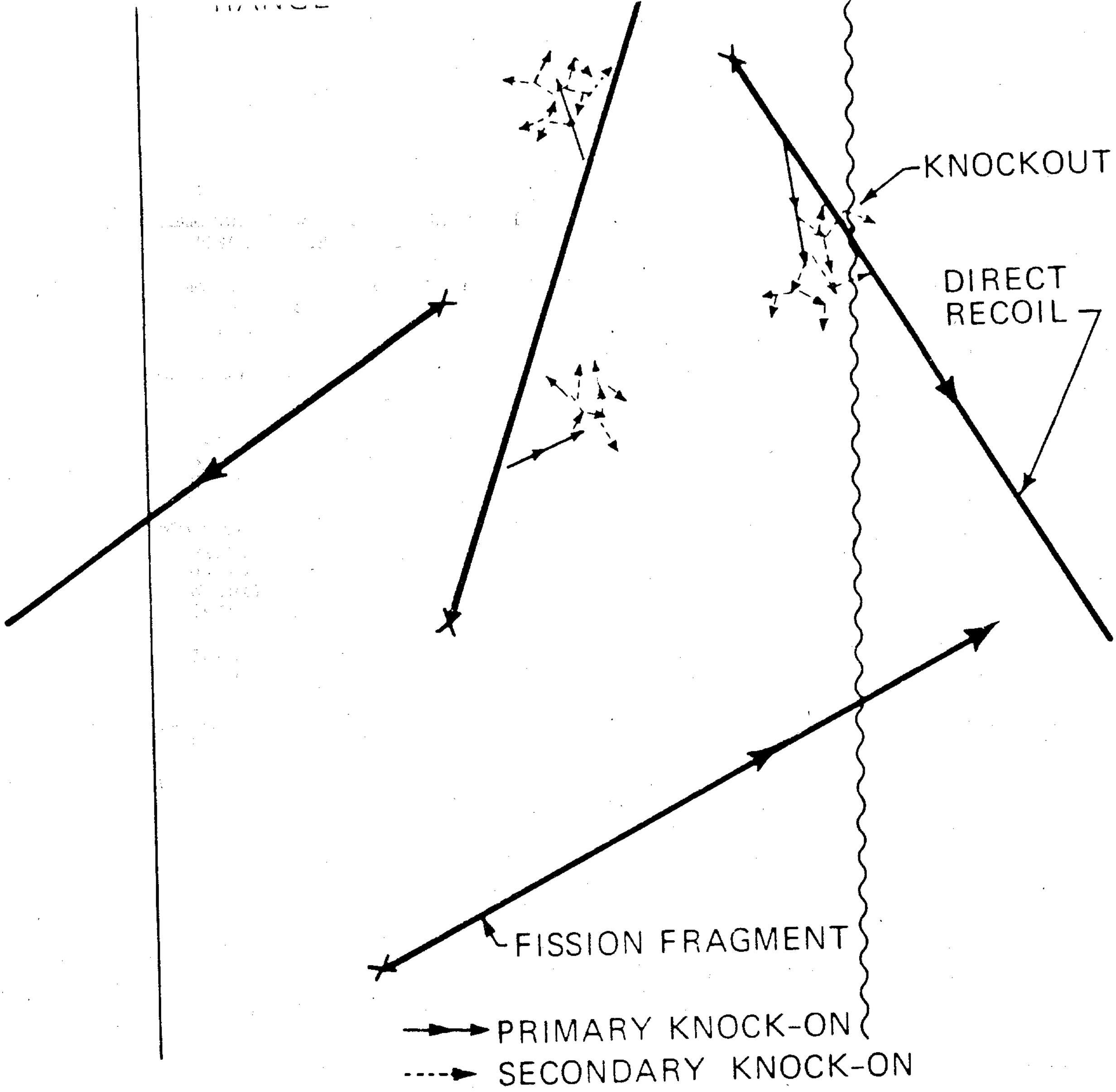

Fig. 15.7 Fission-gas release by direct recoil and knockout.

Table 15.1 Characteristics of Fission Fragments and Knock-ons in UO_2*

Particle	Number created per fission fragment	Mean energy, keV	Range, Å
Fission fragment	1	80,000	100,000
Primary uranium knock-ons	28	100	220
Higher order uranium knock-ons	21,000	0.2	44

$$q_i = \frac{1}{2}\left(1 + \left[\frac{x}{\mu}\right]\right)P_i \qquad 0 \le x \le \mu$$

$$q_i = P_i \qquad x \ge \mu$$

$$I_i = \frac{P_i \mu}{4} \qquad x=0 \qquad \text{Not simple!}$$

15.3.1 Direct Recoil - Read

$$\frac{dC_i}{dt} = \frac{1}{2}\left(y_i \dot{F}\right)\left(1 + \frac{x}{\mu_{ff}}\right) - \lambda_i C_i \qquad 0 \le x \le \mu_{ff}$$

$$\frac{dC_i}{dt} = \left(y_i \dot{F}\right) - \lambda_i C_i \qquad x \ge \mu_{ff}$$

$$I_i^{rec} = \frac{Y_i \dot{F} \mu_{ff}}{4} \qquad \text{See Fig 15.11}$$

15.3.2 Knockout of Matrix Atoms - Read

$$I_{ff}^{rec} = \frac{1}{4}\left(2\dot{F}\right)\mu_{ff}$$

15.3.3 FP Release by the Knockout Mechanism - Read

15.3.4 Short Lived Fission Products -Read

$$q_i^{ff} + q_i^{KO} = P_i + \lambda_i C_i$$

Stopping of FF	Knock in	Knock out	Decay

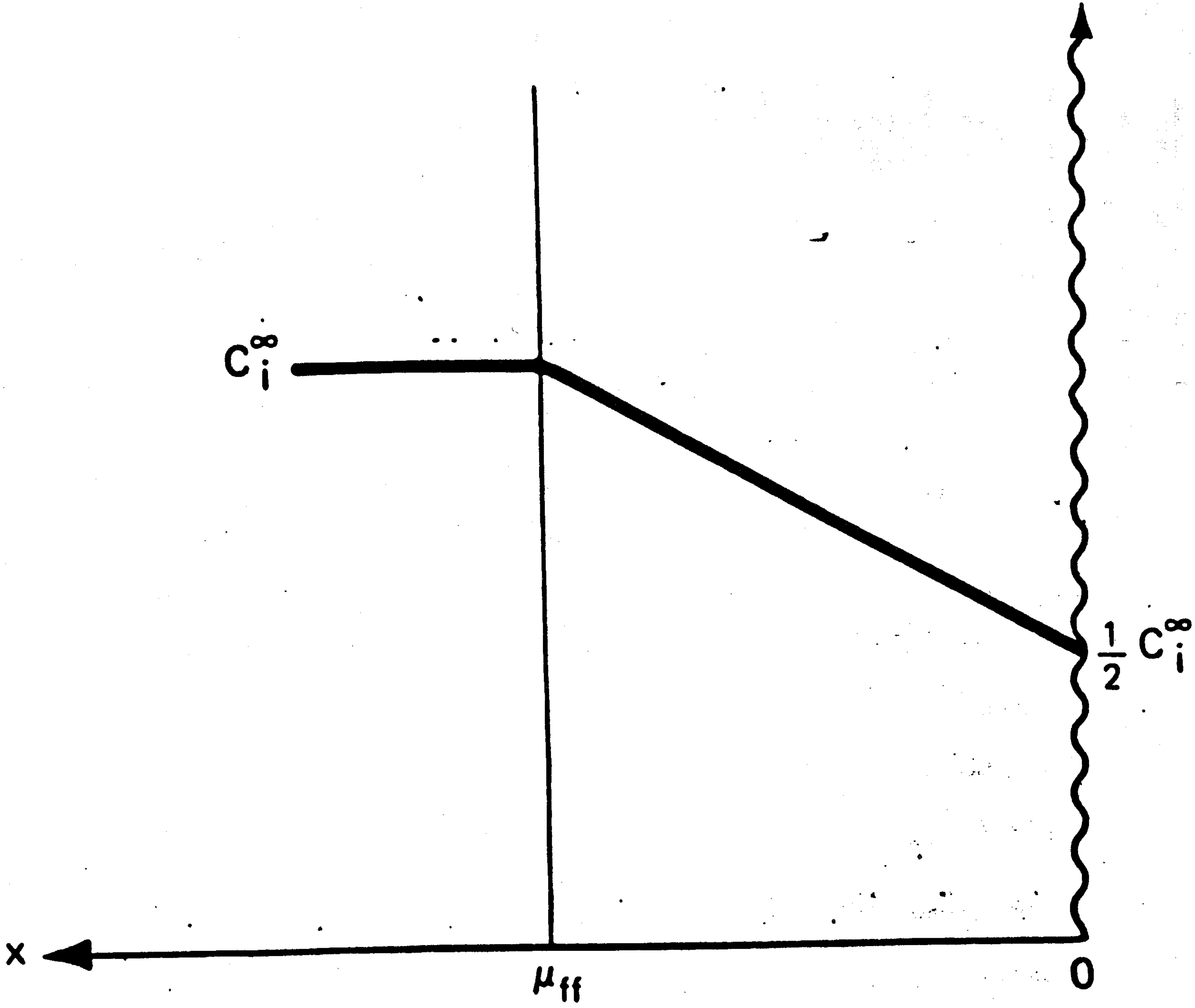

Fig. 15.11 Concentration of fission product i near the surface

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<u>15.3.5</u> <u>Release</u> <u>of</u> <u>Short</u> <u>Lived</u> <u>Isotopes</u> <u>Due</u> <u>to</u> <u>Surface</u> <u>Fissions</u> - Read

<u>15.3.6</u> <u>Stable</u> <u>Fission</u> <u>Products</u> - Read

15.4 Equivalent Sphere Model of Diffusional Release

1.) **Simple Diffusion**
2.) **Effect of Trapping**
3.) **Resolutioning**

15.5 Simple Diffusion

15.5.1 Post irradiation Annealing

(assume Kr ≈ Xe)

$$\frac{\partial C}{\partial t} = D\left\{\frac{1}{r^2}\left[\frac{\partial\left(r^2\frac{\partial C}{\partial r}\right)}{\partial r}\right]\right\} \qquad \textbf{Fick's Law}$$

$$f = \frac{6}{\sqrt{\pi}}\sqrt{\frac{Dt}{a^2}} \qquad a \equiv \text{radius of grain}$$

fractional release

$$f = \frac{6}{\sqrt{\pi}}\sqrt{D't}$$

15.5.2 In Pile Gas Release

$$\frac{\partial C}{\partial t} = Y\dot{F} + D\frac{1}{r^2}\left[\frac{\partial\left(\frac{r^2\,\partial C}{\partial r}\right)}{\partial r}\right] - \lambda C$$

$$f = 4\sqrt{\frac{D't}{\pi}} \quad \text{for } f < 0.3$$

15.5.3 Fission Gas Release in a Fuel Element

$$\overline{\overline{f}} = 3\sqrt{\frac{\overline{\overline{D'}}}{\lambda}}$$

$\overline{\overline{D}}$ is empirical diffusion coefficient averaged over radius and length (Figure 15.16)

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15.6 Diffusion With Trapping

Figure 15.17

1.) Natural Defects
  - **a.) Grain boundaries Figure 15.19**
  - **b.) Dislocation lines**
  - **c.) Closed pores in as - fabricated fuel**
  - **d.) Impurities in solid**

2.) Radiation Produced Defects
  - **a.) Vacancy Clusters**
  - **b.) Interstitial loops**
  - **c.) Fission gas bubbles**
  - **d.) Solid fission product precipitates**

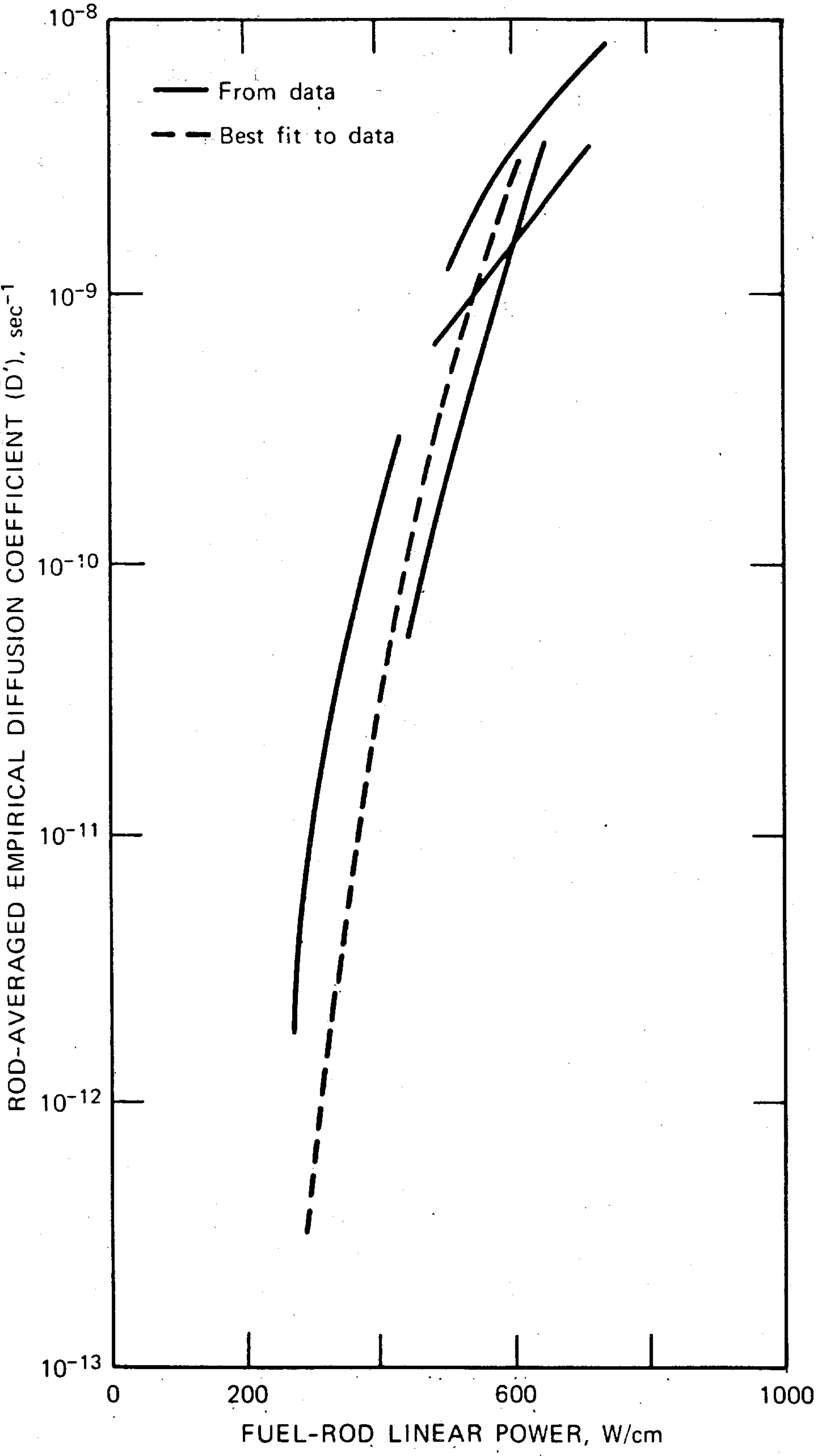


Fig. 15.16 Rod-averaged empirical diffusion coefficients obtained from AECL (Atomic Energy of Canada, Ltd.) rod-puncture data. (From Ref. 16.)

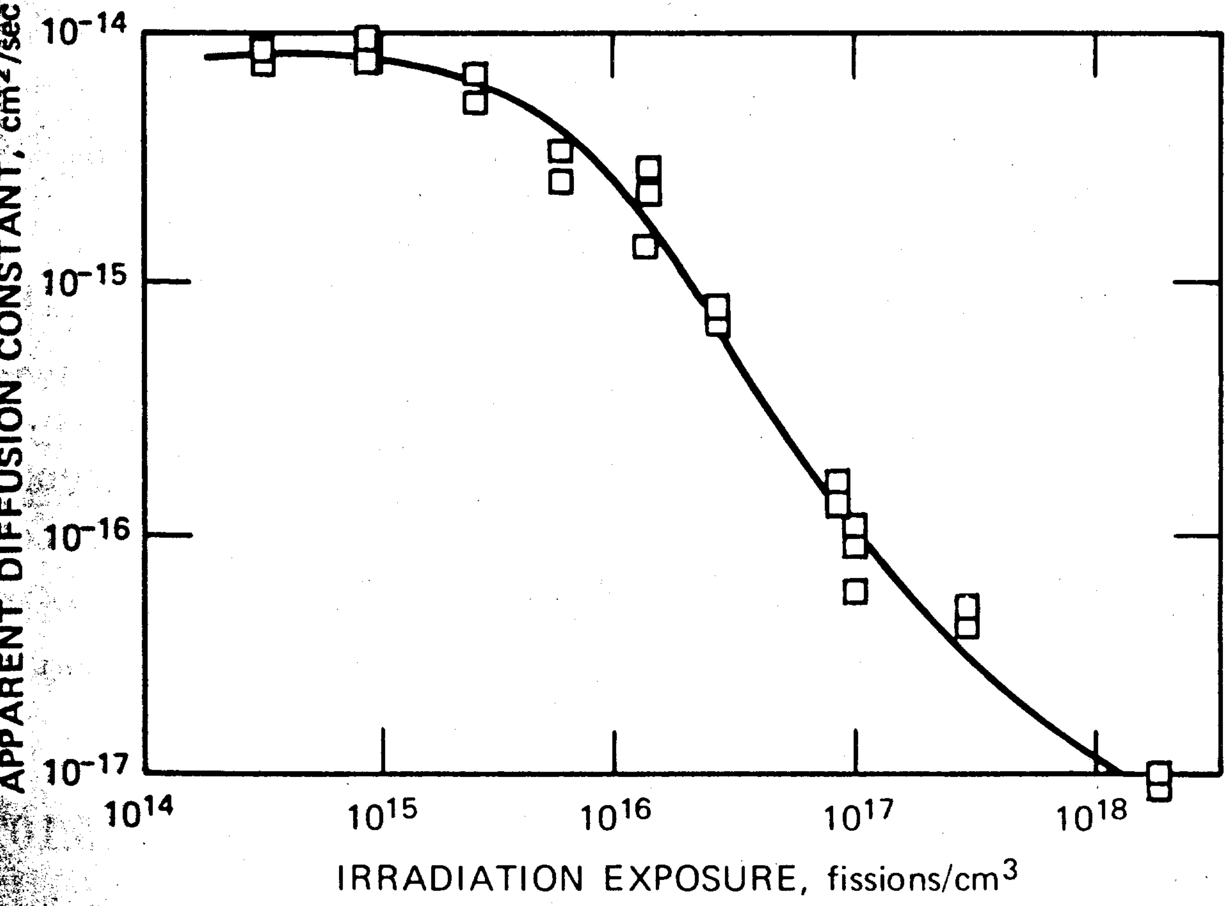
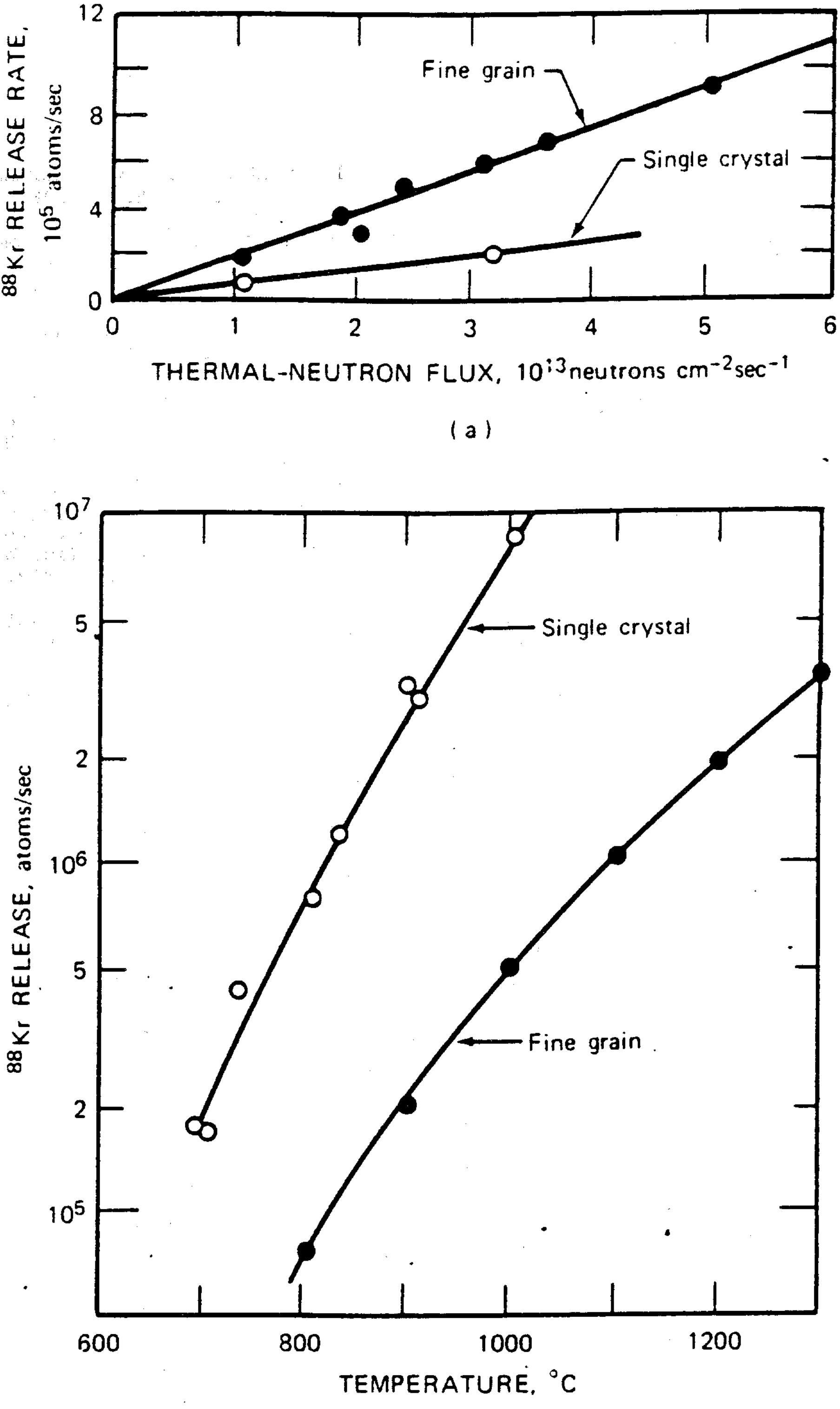


Fig. 15.17 Variation of the apparent diffusion coefficient of fission gases in single-crystal UO_2 with prior irradiation exposure (at low temperature). Postirradiation annealing conducted at 1400°C. [From J. R. MacEwan and W. H. Stevens, *J. Nucl. Mater.*, 11: 77 (1964).]



(a)

(b)

Fig. 15.19 Comparison of ^{88}Kr release rates from single-crystal and polycrystalline UO_2 at (a) low temperature and (b) high temperature. The specimens in (a) had the same geometric surface area, and the release rates in (b) were normalized to the same geometric surface area. [After R. M. Carroll and O. Sisman, *Nucl. Appl.*, 2: 142 (1966).]

15.7 Gas Accumulation in Grain Boundary Bubbles

Speight model(Fig. 15.22 a&b)

Tries to determine how much gas is ;

- ***a.) in grain bubbles***
- ***b.) in grain solution***
- ***c.) in between GB's***

Full expression is in eq. 15.179

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with substantial resolutioning

$$f_{gb} = 3\left(\frac{D}{a^{2}b}\right)\left(\frac{a}{\mu_{Xe}^{KO}}\right) \qquad (15.182)$$

Apparent diffusion coefficient	***radius of equivalent sphere***	***Resolution coefficient***	***Range of Knock*** **on in fuel**

This model is not too useful because it only treats grain boundaries in tact.

15.8 Breakaway Gas Release Due to Bubble Interconnection

15.8.1 Intragranular Bubbles

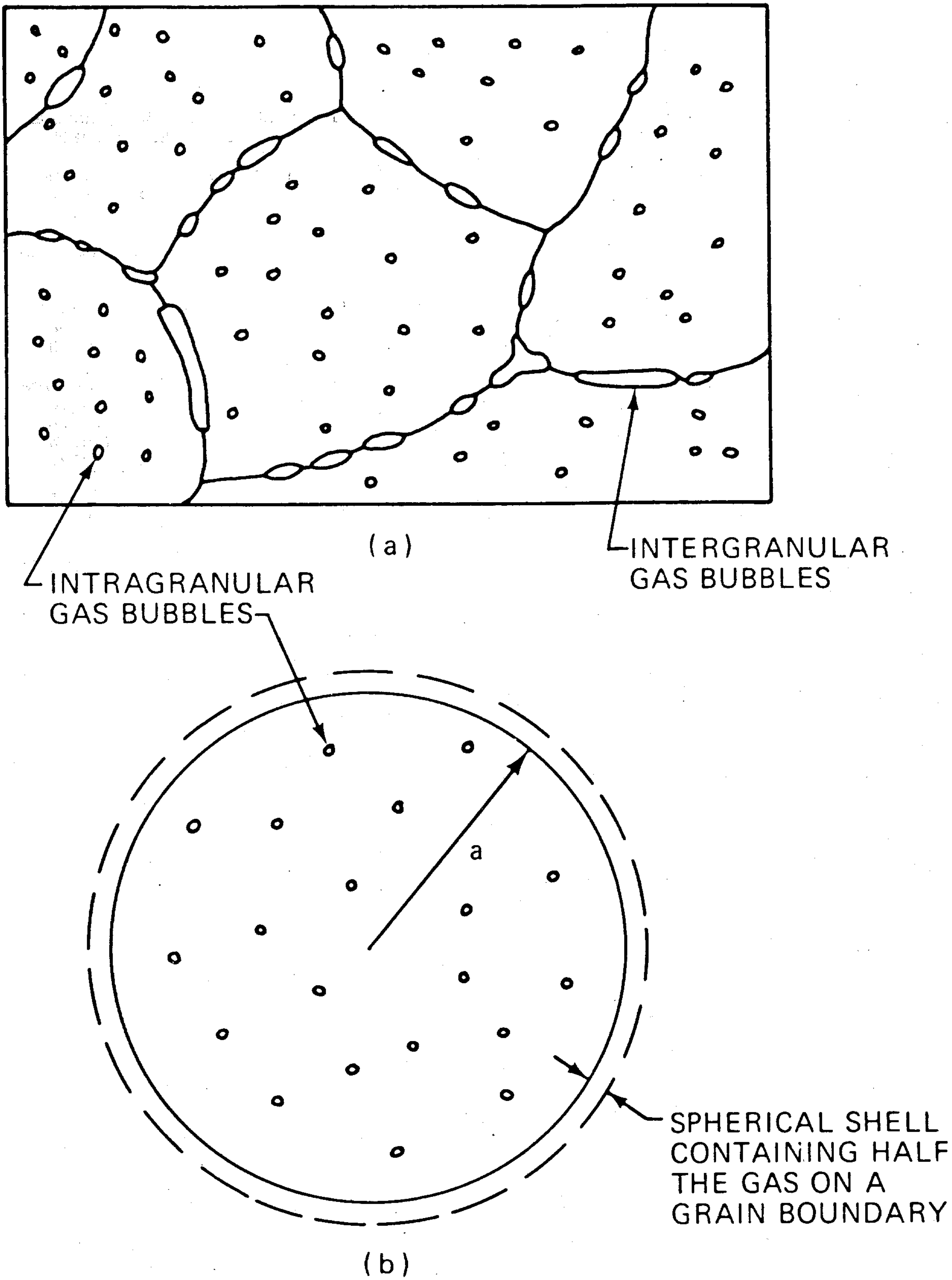
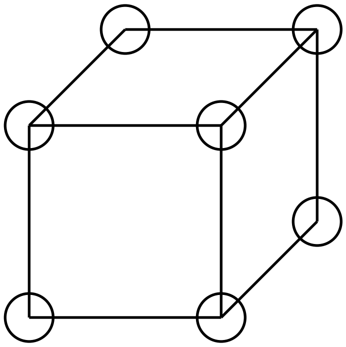


Fig. 15.22 Gas bubbles in grains and on grain boundaries. (a) Actual configuration. (b) Idealized grain used in the model of Speight et al.[25,26]

Set up unit cell to figure when bubbles touch



Each bubble contributres $\frac{1}{8}$ to cube (No GB bubbles)

Critical Porosity for $= \left(\frac{R}{\ }\right)^3_{crit} = \frac{\left(\frac{4\pi R^3}{3}\right)}{(2R)^3}$

Breakaway porosity $= \frac{\pi}{6} = 52\% \quad \frac{\Delta V}{V} = \frac{\left(\frac{R}{\ }\right)^3}{1 - \left(\left(\frac{R}{\ }\right)^3\right)}$ **110%**

However, breakaway swelling would occur at an even earlier value because of random distribution of bubbles.

15.8.2 Grain Boundary Bubbles

Use same approach as earlier but set up equivalent circles on grain boundary, subject to

$$\left(\pi \ _{gb}^{2}\right) N_{gb} = 1$$

$_{gb}$ **= radius of circle containing one bubble**

R_{gb} = radius of bubble

If we use a cubic array on the surface;

$$\left(\frac{R_{gb}}{{}_{gb}}\right)^{2}_{crit} = \frac{\pi}{4}$$

This is > 75% of surface and corresponds to 46 % of V_o

Point of previous comparison is that breakaway swelling value is lower for grain boundaries than for the bulk.

Next question is how do bubbles get to grain boundaries ?

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)

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

(15.205)

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

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

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

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

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

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

See figure 15.30

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

Gas released per

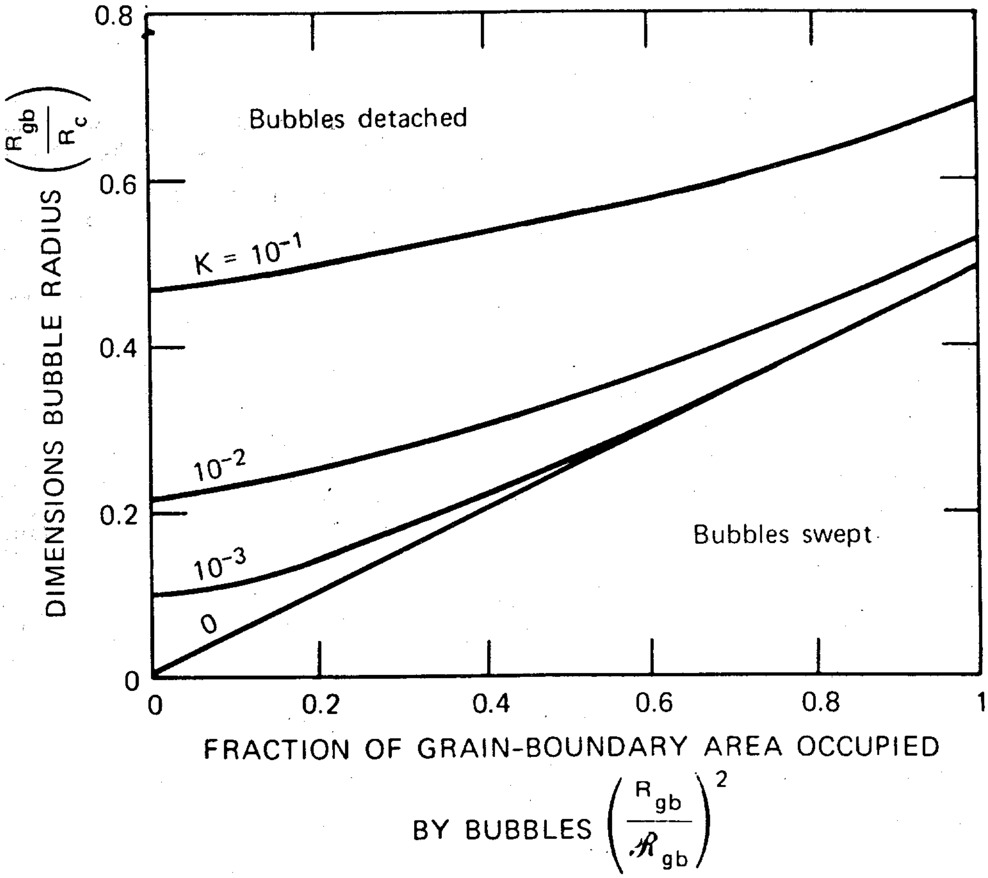

Fig. 15.25 Bubble—grain-boundary stability plot.

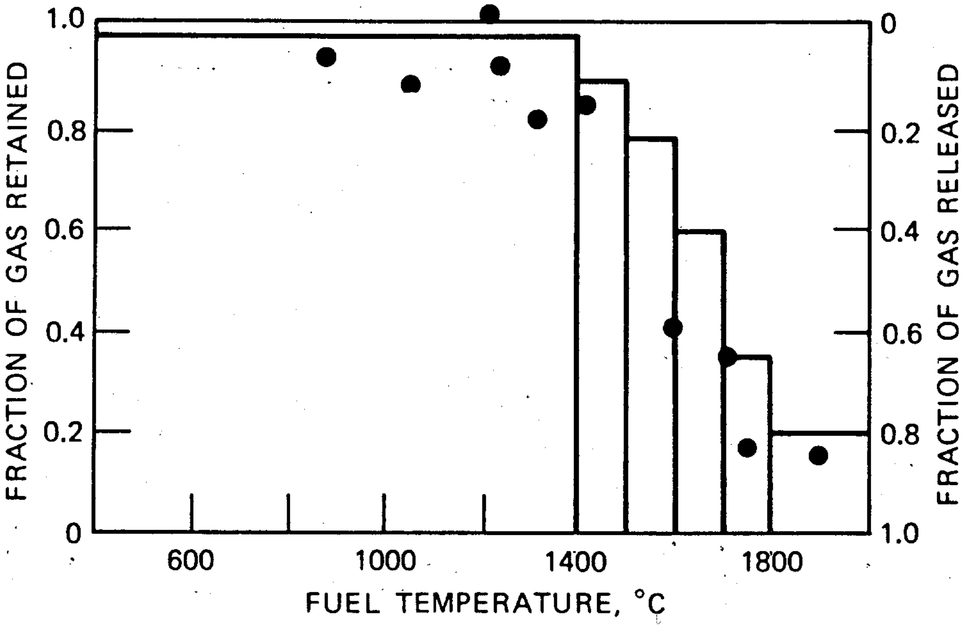

Fig. 15.29 Fission-product gas retention—release in UO_2 as a function of irradiation temperature; points represent measured gas contents of small samples; the histogram is the analytical gas—release function used in the computations. (From Ref. 40.)

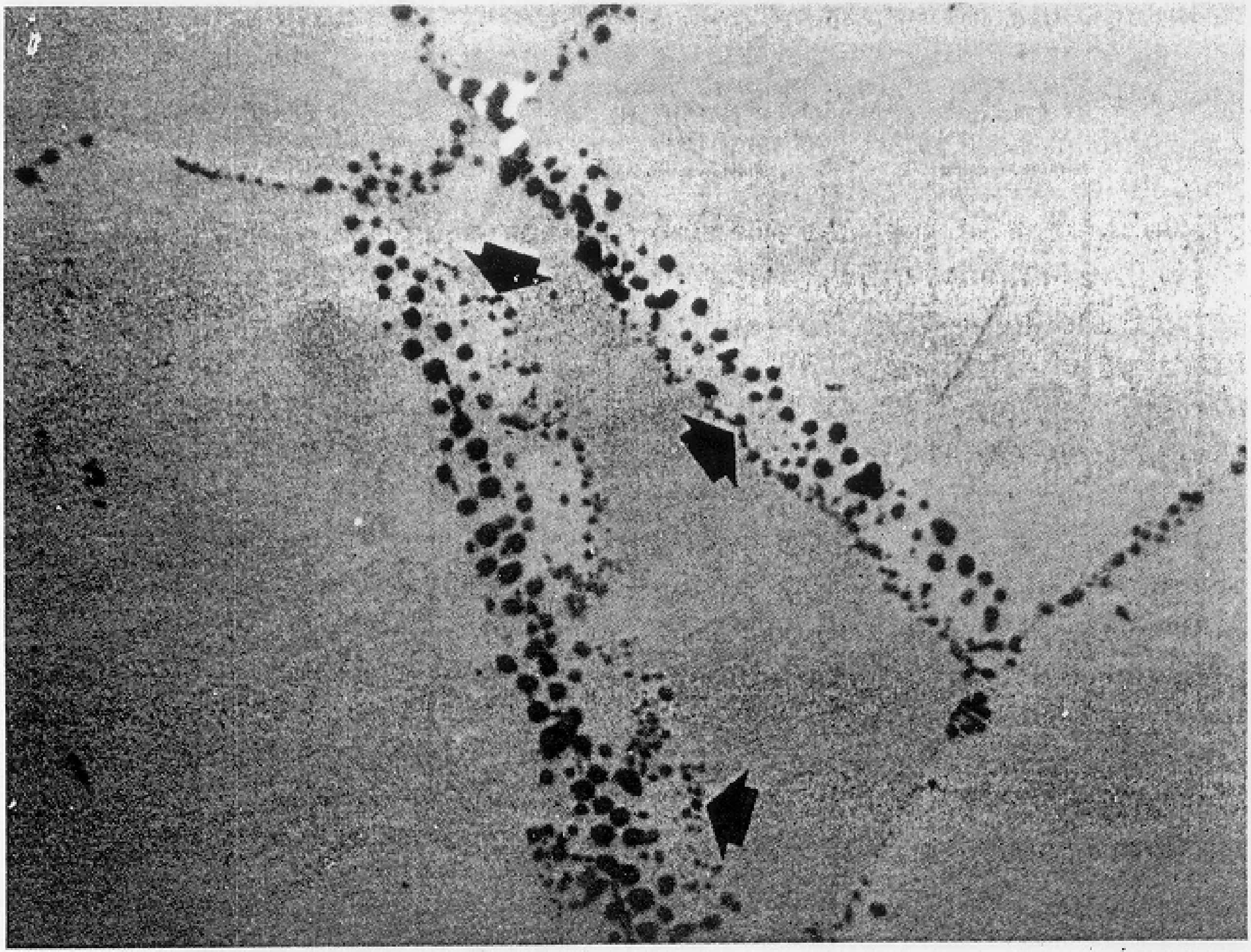

Fig. 15.26 Photomicrograph of a specimen of UO_2 irradiated at 835°C. The small bubbles in the string of bubbles outlining the present position of the grain boundary (arrows) are approximately 0.6 μm in radius. The larger bubbles of about 1.4 μm in radius mark the earlier positions of the boundary. The bubble spacing is ~4 μm. [From R. D. MacDonald, *J. Nucl. Mater.*, 22: 109 (1967).]

$$\textit{unit length of fuel} = Y_{Xe}\left(\overset{\Sigma}{Ft}\right)_{1} \pi R^{2}\,\overline{f}\,(\wp_{1})$$

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Igore the rest of the section

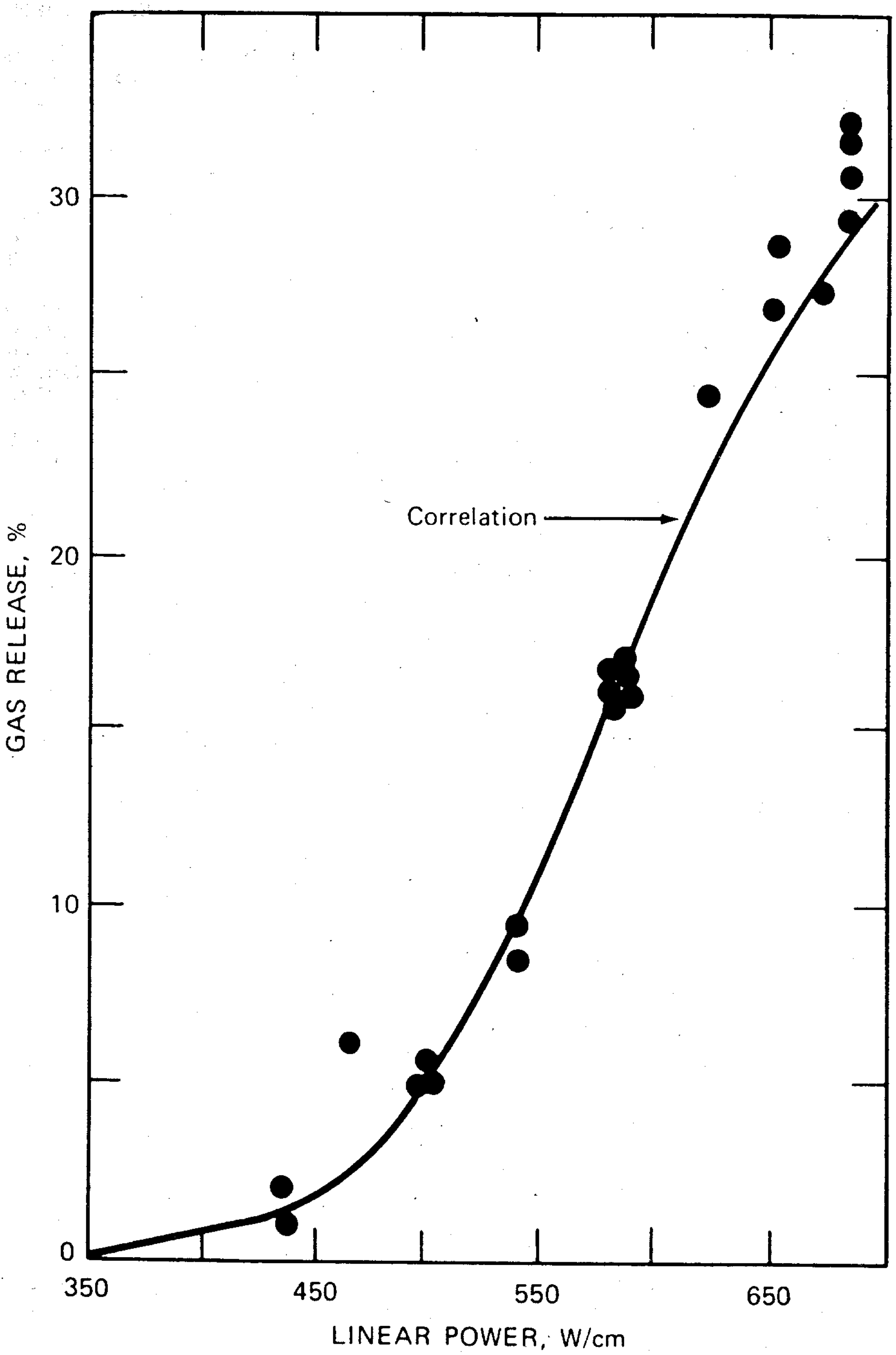

Fig. 15.30 The AECL fission-gas release correlation for thermal (water) reactors. (From J. R. MacEwan et al., in *Proceedings of the Fourth International Conference on the Peaceful Uses of Atomic Energy*, Vol. 10, p. 245, United Nations, New York, 1971.)