3. Introduction to Microstructural Evolution in Crystalline Materials
How Does Microstructural Evolution Occur in a Material Under Irradiation?

1. Irradiation produces interstitial and vacancy point defects in the lattice.

2. Interstitial and vacancy point defects often have high mobilities and readily diffuse through the crystal lattice.

3. These freely-migrating point defects combine to form higher-order point defect complexes.

4. This point defect condensation process progresses continuously into a nucleation & growth process of extended defect clusters.

5. Interstitial clusters become interstitial loops.

6. Vacancy clusters become either vacancy loops or voids.

7. This microstructural evolution leads to property changes such as embrittlement and macroscopic swelling
Volumetric swelling versus fast neutron fluence for two engineering ceramic oxides: $\alpha$-Al$_2$O$_3$ and MgAl$_2$O$_4$

(also shown in the plot is the displacement damage *dose* in units of displacements per atom (*dpa*))

Schematic diagrams showing effects of irradiation on annular cylinders of two engineering ceramic oxides:

(a) $\alpha$-Al$_2$O$_3$ and (b) MgAl$_2$O$_4$
Examples of Swelling

Ref: Garner, Ch. 6, Irradiation Performance of Cladding and Structural Steels in Liquid Metal Reactors, of “Nuclear materials part 1”, Vol 10A, Published by VCH, Germany

Figure 6-24. Easily observed swelling (≈10% linear, ≈33% volumetric) in unfueled 20% cold worked AISI 316 cladding tube at $1.5 \times 10^{23}$ n cm$^{-2}$ ($E > 0.1$ MeV) or ≈75 dpa at 510°C in EBR-II (after Straulsnud et al., 1982). Note that, in the absence of physical restraints, all relative proportions are preserved during swelling.

Figure 6-131. (a) Top of a bundle of D9 fuel pins irradiated to a peak fluence of $2.1 \times 10^{23}$ n cm$^{-2}$ ($E > 0.1$ MeV), showing varying length of pins in response to gradients across the bundle in flux and temperature and also to small variations in pin fabrication history and composition. (b) An undistorted fuel pin assembly with nonswelling HT9 cladding at $1.9 \times 10^{23}$ n cm$^{-2}$ ($E > 0.1$ MeV) (after Makenas et al., 1990a).
Schematic diagrams showing atomic level effects of energetic particle irradiation on two engineering ceramic oxides: (a) $\alpha$-$\text{Al}_2\text{O}_3$ and (b) MgAl$_2$O$_4$.

Instantaneous damage corresponds to approximately a femtosecond ($10^{-15}$ s) after a particle-solid interaction, while damage evolution represents the atomic situation after a few picoseconds ($10^{-12}$ s) of evolved time.
Radiation-Induced Swelling

Swelling is one of the most catastrophic consequences of high-dose radiation damage.

Swelling is caused by complicated microstructural changes, especially:
1. Nucleation and growth of *interstitial dislocation loops*

   followed by

2. Nucleation and growth of *voids*

   In certain circumstances where significant transmutation occurs, swelling can be due to the accumulation of bubbles of gas (e.g., He or Xe bubbles).
Radiation-Induced Interstitial Dislocation Loops

Experimental observation of interstitial dislocation loops (electron irradiations)

Al

Cu

Ni

Fe

Zn (basal plane)
Radiation-Induced Voids

Bright-field (BF) transmission electron microscopy (TEM) image showing the microstructure of $\alpha$-$\text{Al}_2\text{O}_3$ following fast neutron irradiation at $T = 1050$ K to a fluence of $3 \times 10^{25}$ n/m$^2$.

The micrograph reveals a high density of small voids (2-10 nm diameter), arranged in rows along the $c$-axis of the hexagonal unit cell for the $\alpha$-$\text{Al}_2\text{O}_3$.

Micrograph courtesy of F. Clinard, Los Alamos National Laboratory.
Radiation-Induced Bubbles

HFIR irradiation at 400 °C to 51 dpa

F82H (36 appm He)

10B-doped F82H (330 appm He)


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\begin{align*}
\frac{10}{5} \text{B} + \frac{1}{0} \text{n} & \rightarrow 3838 \text{ barns} \\
& \rightarrow \frac{7}{3} \text{Li} + \frac{4}{2} \text{He}
\end{align*}
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