What is Currently Being Used in Fission Power Plants Today?

Fuel Element Performance

Fuel
- Metallic Fuel
  - Early U Fuels
  - LMR Fuels
- Oxide Fuel
  - Fuel Chemistry
  - Fission Product Behaviour
  - Swelling
  - Fission Gas Release
  - Pore Migration and Restructuring

Cladding
- Zircalloy

Enrichment
Metallic Fuels

- During first 10 years of fission reactor research almost all fuels were metallic.

- Now (see last lecture) practically all power reactor fuels are oxides.

- Need fissionable isotope $\text{U}^{235}$,

\[ t_{1/2} = 710 \text{ million years} \]

**Uranium Phases**

- $\alpha = \text{orthorhombic} \quad a \neq b \neq c$
- $\beta = \text{tetragonal} \quad a = b \neq c$
- $\gamma = \text{body centered cubic} \quad a = b = c$

(figure)

<table>
<thead>
<tr>
<th>Anisotropy of Alpha Uranium Phase</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice Direction</td>
<td>Å</td>
<td>Thermal Expansion Coefficient $^\circ\text{C}^{-1} \times 10^{-6}$ (25-125)</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>2.852</td>
<td>21.17</td>
<td></td>
</tr>
<tr>
<td>010</td>
<td>5.685</td>
<td>-1.15</td>
<td></td>
</tr>
<tr>
<td>001</td>
<td>4.945</td>
<td>23.2</td>
<td></td>
</tr>
<tr>
<td>Volume</td>
<td>45.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The crystal structure of alpha uranium.

The crystal structure of beta uranium.

Body Centered Cubic

$a_o = 3.524 \text{ Å}

at 805^\circ C$

The crystal structure of gamma uranium.
Dimensional Stability

1.) **Irradiation Growth**
   Change of shape without appreciable volume change

2.) **Irradiation Creep**
   Change of shape under an external stress

3.) **Swelling**
   No change of shape but a change in volume

*Plus two other phenomena NOT related to irradiation!*

A.) **Thermal Racheting**
   Thermal cycling of polycrystal textured specimen in $\alpha$ phase

B.) **Surface Roughing**
   Cycling through the $\alpha$–$\beta$ phase transition
Necessary Definitions

Problem: *What unit to use in describing radiation damage in fissile material?*

Properties are more related to fission events than to neutron fluence

No single definition satisfactory!

A.) Reactor Designer - More concerned with power density than fission density

B.) Reactor Physicist- More concerned with percentage of fissile atoms lost by all processes than with % fissioned

C.) Material Scientists- Can’t agree! i.e., a 70% burnup of U atoms in UO₂ -Steel cermet means more than 3 x 10²¹ fissions/cm³
Deposited in fuel
Total Energy Release

MWd

? t

ton tonne

Total fuel? Just U?

Instantaneous

Design Dependent

Energy per $^{235}$U Fission

169 MeV - FP
5 MeV - n
5 MeV - $\gamma$

12 MeV - FP

8 MeV - $\beta,\gamma$

199 MeV

+ 10-12 neutrinos
Another Unit Which is Misinterpreted -

\[ \frac{\text{Fission}}{cm^3} \]

- Necessary for heat transfer calculations

\[ \text{What is included in cm}^{-3} \ ? \]

*Normally it is not the cladding or the coating on the fuel pellets*

\[
\frac{\text{Fission}}{cm^3} = \left( \frac{\text{frac. of U atoms fissioned}}{\text{density of U in fuel}} \right) \\
= \frac{N_f}{N_U} \cdot \left\{ nvt \sigma_f \right\} \cdot \frac{\rho N_A}{m'}
\]

where;

\[
\frac{N_f}{N_U} = \text{fraction of U atoms that can fission} \\
\rho = \text{fuel density} \\
m' = \text{M. Wt. of fuel/} \# \text{ of U atoms in molecule} \\
N_A = \text{Avogadros Number}
\]
Relate Burn-up and Integral Flux

Let \( N \) = atoms of fissile isotopes
\( \sigma_c, \sigma_f = \) capture and fission cross sections, respectively

\[
\frac{dN}{dt} = -Nnv\sigma_a
\]

where \( \sigma_a = \sigma_c + \sigma_f \)

Integrating and finding the % of fissile atoms lost, one finds;

\[
100 \left\{ \frac{(N_0 - N)}{N_0} \right\} = 100 \left\{ 1 - e^{-nvt\sigma_a} \right\}
\]

The % of atoms fissioned is then;

\[
100 \left[ \frac{\sigma_f}{\sigma_a} \right] \left\{ 1 - e^{-nvt\sigma_a} \right\}
\]

when \( nvt\sigma_a \ll 1 \), \( \exp (-x) \approx 1 - x \),

% atoms fissioned = 100 \( nvt\sigma_f \)

since \( \sigma_f \approx 550 \) barns for \(^{35}\text{U}\) in thermal flux;

% B.U. of \(^{35}\text{U}\) atoms = 55000 \( b \cdot (nvt) \)

If only a fraction of \( U \) atoms are fissionable;

\[
\frac{N_f}{N_U} \left[ 100 \cdot nvt\sigma_f \right]
\]
Example

• Assume 1 fission = 200 MeV

\[
\left(200 \cdot 10^6 \frac{\text{eV}}{\text{fission}}\right) \cdot \left(1.6 \cdot 10^{-19} \frac{\text{watt} \cdot \text{s}}{\text{eV}}\right) \cdot \left(\frac{1\text{day}}{86,400\text{s}}\right)
\]

\[= 3.7 \cdot 10^{-16} \frac{\text{watt} \cdot \text{d}}{\text{fission}}\]

\[\frac{\text{watt} \cdot \text{d}}{\text{g fuel}} = 3.7 \cdot 10^{-16} \cdot \left(\frac{1}{\rho_{\text{fuel}}}\right) \cdot \left(\frac{\text{fissions}}{\text{cm}^3}\right)\]

or, \[\frac{\text{MWd}}{\text{tonne} - \text{U}} = 3.7 \cdot 10^{-16} \cdot \left(\frac{1}{\rho_{\text{fuel}}}\right) \cdot \left(\frac{\text{fissions}}{\text{cm}^3}\right) \cdot \frac{m'}{A}\]

where \(A = \text{atomic wt. of U}\)

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What if not all of the energy released is captured by the fuel?

• can only count on 169 MeV K.E. of FP's

Plus 12 MeV Decay of FP's

\[\frac{\text{MWd}}{\text{tonne} - \text{fuel}} = 1.85 \cdot 10^{-18} \cdot \left(\frac{1}{\rho_{\text{fuel}}}\right) \cdot \left(\frac{\text{fissions}}{\text{cm}^3}\right) \cdot E_f\]

where \(E_f\) is the fission energy (MeV) deposited in the fuel
Another way to express this is:

\[
\frac{\text{MWd}}{\text{tonne} - \text{U}} = 1.85 \times 10^{-18} \left( \frac{E_f}{\rho_{\text{fuel}}} \right) \left( \frac{\text{fissions}}{\text{cm}^3} \right) \cdot \frac{m'}{A}
\]

What Have We Forgotten?

1.) Conversion of fertile to fissile
   (important at low enrichments and at high burn up)

2.) Fast fission
   Few % in thermal reactors

3.) Absorption of gamma rays
   From the parent fuel rod or from surrounding fuel rods
\[
\frac{MWd \cdot \text{within \ fuel}}{\text{tonne \ fuel}} = \frac{A}{m^*} \cdot (\_)
\]

\[
\frac{MWd \cdot \text{within \ fuel}}{\text{tonne \ U}} = 1.85 \cdot 10^{-18} \left(\frac{m^* E_f}{\rho A}\right) \cdot (\_)
\]

\[
\frac{\text{fissions}}{cm^3} = 6.02 \cdot 10^{21} \cdot \left(\frac{\rho N_t}{m^* N_U}\right) \cdot (\_)
\]

\[
\% \ \text{of \ all \ atoms \ fissioned} = \frac{N_U}{N_t} \cdot (\_)
\]

\[
\% \ \text{of \ all \ U \ atoms \ fissioned} = 100 \frac{N_f \sigma_f}{N_U} \cdot (\_)
\]

\[
\text{neutron \ \text{fluence} \ = \ nvt}
\]