Basics of Nuclear Fuels

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Outline of Presentation

- What is a Nuclear Fuel?
- Types of Nuclear Fuels
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  - Fuel Assemblies
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- Irradiation Performance Phenomena
  - High temperature gradient
  - Burnup and fission product accumulation
  - Irradiation growth
  - Fuel swelling and fuel-cladding mechanical interaction (FCMI)
  - Fission gas release
  - Fuel constituent redistribution
  - Fuel restructuring
  - Fuel-cladding chemical interaction (FCCI)
  - Fuel-coolant compatibility
  - Cladding swelling, creep, corrosion
What is a Nuclear Fuel?

- Nuclear fuel is a (usually removable) component that includes fissile and/or target material used as the power source to achieve and sustain a controlled nuclear chain reaction
  - It must survive the reactor environment without allowing any significant release of radioactive materials

- **Fissile Materials:**
  - $^{235}\text{U}$ is the only naturally occurring fissile isotope
  - **Natural uranium** contains 0.7 wt% $^{235}\text{U}$ and 99.3 wt% $^{238}\text{U}$
  - Targets of $^{238}\text{U}$ produce fissile $^{239}\text{Pu}$ by neutron capture
  - Targets of $^{232}\text{Th}$ produce fissile $^{233}\text{U}$ by neutron capture
  - Other actinides also include fissionable isotopes

- **Nuclear fuel elements normally include:**
  - The fissile and/or target material in a stable form
  - A cladding barrier to contain the fissile material and fission products and prevent interaction with reactor coolant
  - An assembly structure to fit the reactor design allowing load and unload
Types of Nuclear Fuels

- **Nuclear fuels differ widely from reactor to reactor**
  - Geometrical configuration of fuel and cladding
    - *Fuel rods*
    - *Fuel plates*
    - *Particle fuels*
  - Materials used for U-bearing (or Pu) fuel
    - *Ceramic compounds*
    - *Metallic alloys*
  - Materials used for cladding
Fuel Element Designs

- **Rod-Type Fuels**
  - Most common fuel type (i.e., LWRs, LMRs, TRIGAs)
  - Cylindrical fuel in cladding tube
  - Plenum for fission gas

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**EBR-II Mark-II driver-fuel element**

**Fuel rod of a pressurized-water reactor.**
Fuel Element Designs

Plate-Type Fuels
- Research and test reactors (HFIR, MTR, ATR)
- Dispersion fuels (i.e., fuel particles embedded in a metal matrix)
- No plenum
Fuel Element Materials

Desirable Properties
- High thermal conductivity
- High melting point
- Low thermal expansion
- Chemically stable
- Resistant to radiation damage
- High fissile density
- Economical fabrication

There is No Perfect Fuel
- Compromise is always required

Fuel Materials
- Ceramic Compounds
  - Oxides \( \{UO_2, (U,Pu)O_2\} \)
  - Carbides \( \{UC, (U,Pu)C\} \)
  - Nitrides \( \{UN, (U,Pu)N\} \)
- Metal Alloys (U-Pu-Zr-Mo)
- Others (UA\(_x\), U\(_3\)Si\(_2\), U/Zr hydride)

Cladding Materials
- Zirconium Alloys for LWRs
- Stainless Steels for Fast Reactors
- Aluminum Alloys for Research and Test Reactors
- SiC for Gas Reactors
- Refractory Alloys for High Temperature Applications (i.e., W, Ta, Nb, Mo, V)

Bond (Gap) Materials
- Helium gas
- Liquid sodium
- Metallurgical bond (i.e., no gap)
Fuel Forms

- **Oxide Fuels** – Nominally UO$_2$
- **Metallic Fuels**
  - Pure U metal
  - U – Al alloys
  - U – Zr alloys
  - U – Mo alloys
- **Dispersion Fuels** [metallic compounds or ceramics in a metal matrix]
  - UAl$_x$-Al
  - U$_3$Si$_2$-Al
  - U-ZrH
- **Particle Fuels** – UO$_2$ or UO$_2$+UC$_2$
  [ceramic spherical particles with ceramic barrier coatings in a graphite or ceramic matrix]
Fuel Assemblies – Reactor Core Fuel Arrays

- Fuel Assemblies are arrays of fuel pins or rods spaced and framed with hardware, sometimes with control rods, for direct insertion into reactor cores.

- Fuel assemblies are specific to the reactor design involved.

Mitsubishi PWR Fuel Assembly Configuration
Other Fuel Assemblies

- TRIGA Cluster
- TRIGA MK 1 & II
- CANDU
- BWR
Other Fuel Assemblies

Prismatic HTGR

Pebble Bed HTGR

Single Pass

MAGNOX

RBMK
Other Fuel Assemblies

**Sodium Fast Reactor**
Fabrication Issues

- **Ceramic Fuels**
  - Pellet fabrication non-trivial
  - Powder processing
    - pressing, sintering, grinding of pellets
    - tight tolerances

- **Metallic Fuels**
  - Relatively easy to fabricate by melting/casting processes

- **Dispersion Fuels**
  - Make, mix and press fuel and matrix powders
  - Roll or co-extrude with cladding

- **Particle Fuels**
  - Complex fabrication process
  - Aqueous synthesis of fuel kernels
  - CVD application of coatings
  - Compacting with matrix material
During irradiation of a nuclear fuel, many complex and interrelated phenomena occur:

- High temperature gradient
- Burnup and fission product accumulation
- Irradiation growth
- Fuel swelling and fuel-cladding mechanical interaction (FCMI)
- Fission gas release
- Fuel constituent redistribution
- Fuel restructuring
- Fuel-cladding chemical interaction (FCCI)
- Fuel-coolant compatibility
- Cladding swelling, creep, corrosion

These phenomena degrade the nuclear fuel eventually requiring its discharge from the reactor.
**Fuel Temperatures/Temperature Gradient**

- **Oxide Fuels**
  - Low thermal conductivity
    - High central temperature
    - Large thermal gradient
  - High melting point
    - $> 2800^\circ C$

- **Metallic Fuels**
  - High thermal conductivity
    - Low central temperature
    - Small thermal gradient
  - Low melting point
    - $1100-1200^\circ C$
    - Eutectics even lower
Burnup and Fission Products

**Burnup**
- A measure of how much U (or Pu) has been fissioned
  - Units of MW-days/ton-U or atomic-%
  - LWR fuel currently limited to ~50,000 MWD/ton; experiments to >70,000 MWD/ton
  - Metallic & oxide fuel (fast reactors) limited to ~10 at.-%; experiments to 20 at.-%
  - Dispersion fuel (HEU research reactors) limits ~50 at.-%
  - 50-90% of useful U (Pu) atoms not burned → motivation for reprocessing

**Fission Products**
- Two atoms replace every U (or Pu) atom that fissions
- More than 30 chemical elements produced by fission; chemical state of fuel can evolve substantially during irradiation
- 25% of fission products are gas atoms (Kr, Xe)
- Fuels with high minor actinide (Am, Cm) content also produce significant quantities of He during irradiation
Axial growth of fuel column can be significant reactivity effect
- Can influence with alloying additions
- Must understand to ensure adequate excess reactivity for desired cycle length

Axial Fuel Growth, from Pahl et al, 1990
Swelling/Fission Gas Release

- **Fuel Swelling**
  - Fuel swells due to generation of fission products
  - Gas atoms coalesce into bubbles, accelerating swelling
  - Fuel swelling tends to reduce or close gap

- **Fission Gas Release**
  - Some fission gas escapes fuel
  - Pressurizes plenum
  - Percent of gas escaping fuel
    - < 10% in LWR fuel
    - > 50% in fast reactor fuel
Metallic Fuel Behavior—Swelling & Restructuring

As fabricated U-20Pu-10Zr

- X423A at 0.9% BU
- X419 at 3% BU
- X420B at 17% BU

- Zr-rich phases
- 50 μm

- Redistribution of U and Zr occurs early
- Inhomogeneity doesn’t affect fuel life
Metallic Fuel Behavior—Swelling & Gas Release

- **Swelling**
  - Low smear density fuels
  - Rapid swelling to 33 vol% at ~2 at.% burnup

- **Gas Release**
  - Inter-linkage of porosity at 33 vol% swelling results in large gas release fraction
  - Decreases driving force for continued swelling

U-19Pu-10Zr (γ-phase) at 2 at.% burnup
Fuel-Cladding Mechanical Interaction

- Fuel swelling and/or cladding creepdown closes gap
- Continued swelling/creep stresses cladding
- Cladding strain eventually results in failure
Metallic Fuel Behavior—Fuel Constituent Redistribution

U-Pu-Zr

U-Pu-Am-Np-Zr

Lower Melting Phase
MOX Fuel Behavior—Restructuring

MOX fuel ceramography of FFTF driver fuel produced by Kerr-McGee and Babcock and Wilcox, showing restructuring as a function of burnup.  (from Hales, et al, 1986)
- MOX fuel operated at high temperature and undergoing restructuring exhibits high gas release.

(from Lambert, et al, 1994)
Metallic Fuel Behavior—Steady-state FCCI

**Fuel-Cladding Inter-diffusion**
- RE fission products (La, Ce, Pr, Nd) and some Pu reacts with SS cladding
- Interaction product brittle
- Considered as cladding wastage

U-19Pu-10Zr with D9; 12 at.% burnup (from Pahl, et al, 1990)
Transient Phenomena—Metallic Fuels
Fuel/Cladding ‘Eutectic’ Formation

U-10Zr / HT9 at 800°C, 1 hr
(from H. Tsai, et al, 1990)

1 - Unaffected cladding
2 - Fuel/cladding solid-state interaction
3 - Fuel/cladding liquid phase
MOX Fuel Behavior—Fuel-coolant Compatibility

- Run-beyond-cladding-breach (RBCB) of MOX accompanied by fuel/Na reaction and initial crack extension
- Fuel loss can be related to degree of interaction
- Reactant layer can becomescoherent and mitigate further reaction with coolant

Typical breach extension in induced midlife failure, EBR-II K2B test.
(from Lambert, et al, 1990)
Cladding Performance

- Cladding integrity assures fission product containment
  - Breach of cladding referred to as fuel “failure”
  - Failure generally precludes continued use of fuel element/bundle

- Cladding integrity degrades during irradiation
  - Temperature, pressure and neutron flux cause “creep”
    - High coolant pressure causes creepdown (LWRs)
    - High fission gas release causes outward creep (LMRs)
  - Radiation damage causes swelling (embrittlement)
  - Corrosion by coolant
  - Interaction with fuel
Life-Limiting Phenomena

- Cladding breach ends a fuel element’s use
- Cladding breach occurs due to:
  - Embrittlement of zirconium cladding due to corrosion/hydriding by water coolant and stresses induced by FCMI (LWRs) → motivates development of corrosion-resistant cladding alloys
  - Creep rupture of cladding due to fission gas pressurization, accelerated by cladding thinning due to FCCI (LMRs) → motivates development of creep-resistant cladding alloys
- Fuel burnup limit established to preclude cladding breach during irradiation
QUESTIONS?