Introduction to Nuclear Fuel Cycle and Advanced Nuclear Fuels

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The Evolution of Nuclear Power

Nuclear Energy

Generation I

Early Prototype Reactors
- Shippingport
- Dresden, Fermi I
- Magnox

Generation II

Commercial Power Reactors
- LWR-PWR, BWR
- CANDU
- VVER/RBMK

Generation III

Advanced LWRs
- ABWR
- System 80+
- AP00
- EPR

Generation IV

Near-Term Deployment
- Generation III+
  - Highly Economical
  - Enhanced Safety
  - Minimal Waste
  - Proliferation Resistant

Timeline:
- Gen I (1950-1960)
- Gen II (1970-1990)
- Gen III (2000-2010)
- Gen III+ (2020-2030)

- Atoms for Peace
- TMI-2
- Chernobyl
- Fukushima
Meeting the growing energy demand of developing nations by clean energy forms is essential.

- Energy use will grow as developing countries achieve affluence.
- Affluence in developing countries will lead to more stable and peaceful world.
- 10 billion people consuming energy like us result in world energy demand increasing by 10 fold.
- Increased use of fossil fuel will result in
  - Resource shortfalls and regional conflicts,
  - Serious environmental impact
- Worldwide expansion of nuclear energy use is a natural development.
- Nuclear material management is an important International issue.

<table>
<thead>
<tr>
<th>U.N. Human Development Index</th>
<th>Annual electricity use kWh/capita</th>
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<tbody>
<tr>
<td>1.0</td>
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<td>8000</td>
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<td>0.5</td>
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- Pakistan
- India
- Russia
- China
- UK
- France
- Japan
- US
- Germany
- Australia
- Canada
- Japan
- US
- Germany
- Australia
- Canada
- India
- Russia
- China
- UK
- France
- Japan
- US
- Germany
- Australia
- Canada

Annual electricity use kWh/capita
Transmutation – the process by which an element is converted to another element by neutron bombardment
Transuranic – elements heavier than uranium (Pu, Am, Np, Cm, etc. . . .)
Minor Actinides (MA) – Am, Np, Cm
HLW – High Level Waste
MOX – Mixed oxide (U, Pu)O$_x$ as opposed to UO$_x$
LWR – Light Water Reactor (primarily critical on thermal neutrons)
FR – Fast Reactor (primarily critical on fast neutrons, >1MeV)
Spent Nuclear Fuel (SNF) – Fuel that can not be recycled
Used Nuclear Fuel – Fuel that can be recycled
The Nuclear Fuel Cycle

1. URANIUM MINING AND MILLING to uranium oxide (40O2) stage

2. CONVERSION to UF6 (gas)

3. ENRICHMENT to 3-4% U-235

4. FUEL FABRICATION

5. NUCLEAR POWER STATION

6. STORAGE of spent fuel

7. REPROCESSING of spent fuel to separate wastes

8. VITRIFICATION of 750 kg high-level waste in 5 tonnes of Pyrex glass contained in stainless steel canisters

9. FINAL DISPOSAL of high-level waste

Depleted tails, mostly U238

24t U as enriched UF6

24t U is loaded into the reactor

110t U as fuel fabrication

110t U as natural UF6

170t U as uranium oxide

45-50,000 t of typical ore

750 kg high-level wastes

1000 MWe electricity to community for one year (7 billion kwh)
<table>
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<tr>
<th>Tier</th>
<th>Once-Through Fuel Cycle</th>
<th>Single-Tier Transmutation System</th>
<th>Dual-Tier Transmutation System</th>
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<td>LWR</td>
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<td>Spent Nuclear Fuel</td>
<td>TRU</td>
<td>MOX</td>
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<td>TRU</td>
<td>ADS or FR</td>
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<td>High-Level Waste Repository</td>
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<td>HLW</td>
<td>HLW</td>
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DOE Advanced Fuel Development

**Campaign Mission:** Development and demonstration of advanced fuels (and cladding) to support the sustainable nuclear energy and associated fuel cycles using a goal-oriented science based approach.

- Next generation of LWR fuels with enhanced performance and safety, and reduced waste volume
- FR transmutation fuels *(metallic fuel as baseline)* with enhanced proliferation resistance and resource utilization

Development of advanced tools to support the science-based approach: Characterization & PIE techniques, fabrication processes, in-pile and out-of-pile test design, in-pile instrumentation development
Spent/Used Fuel Storage – What do we do with it now?

- <10 years storage in a water pool

Dry and Transfer to Cask Storage
High Level Waste Disposal

Stable Geology

Engineered Systems

Leave it where it is?
Vitrification - a long term storage option for the minor actinides.

- Used in Europe for Fission Products and minor actinides resulting from reprocessing

- Used for weapons process waste at PNNL

- Recycle of Used Fuel extracting Pu for MOX

- Stored in an engineered facility
Enhanced Accident Tolerant Fuels for LWRs

1979 TMI-2 Loss of Cooling Accident

End-State Core Configuration - 1987

2011 Earthquake, Tsunami, and Station Blackout at Fukushima Dai-ichi NPS

Before the earthquake

After the earthquake (before explosion)

Many structures facing the bay are destroyed
Fuel Behavior Under LOCAs (courtesy Bo Chang)

- Zr Exothermic Reaction
- Hydrogen Generation
- Cladding Embrittlement

Normal operation: 290-345°C

Zr Cladding & Burst: 800°C

Rapid Zr Cladding Oxidation: 1000-1200°C

Stainless Steel Melting Point: 1500°C

Zr-alloy Melting: 1850°C

Core Melt: 2200-2800°C

UO₂ Melting: 1850°C

Control Rod/Blade Collapse: 1500°C

Fuel Surface: 290-345°C
Fuel in Accidents

- **TMI-2 accident in 1979**
  - Fuel failure detected ~2.7 hr after loss of coolant flow
  - 50% core melted in 7 hours
  - Small hydrogen explosion in ~10 hrs, no RPV breach

- **Fukushima Daichi Units 1-3**
  - Some battery-supported cooling after tsunami in Units 2&3, but not Unit 1
  - Hydrogen explosion and RPV pressure drop after ~1 day in Unit 1 and 2-3 days in Units 2 & 3

- Initial core cooling to remove decay heat is critical
- Fuel meltdown by decay heat in ~3 hrs once water flow stops
What are the major issues to be addressed for the attributes?

**Improved Reaction Kinetics with Steam**
- Heat of oxidation
- Oxidation rate

**Improved Fuel Properties**
- Lower operating temperatures
- Clad internal oxidation
- Fuel relocation / dispersion
- Fuel melting

**Slower Hydrogen Generation Rate**
- Hydrogen bubble
- Hydrogen explosion
- Hydrogen embrittlement of the clad

**Improved Cladding Properties**
- Clad fracture
- Geometric stability
- Thermal shock resistance
- Melting of the cladding

**Enhanced Retention of Fission Products**
- Gaseous fission products
- Solid/liquid fission products

**High temperature during loss of active cooling**

Based on these safety-related issues, metrics for quantifying the enhancements in accident tolerance must be developed in conjunction with the safety features of a given LWR design and based on specific accident scenarios.
Enhanced Accident Tolerant LWR Fuel Vision, Mission and Near-Term Goals

Vision:
A LWR fleet with enhanced accident tolerance providing a substantial fraction of the national clean energy needs

Mission:
Develop advanced fuels and non-design intrusive reactor system technologies (e.g. instruments, auxiliary power sources) with improved performance, reliability and safety characteristics during normal operations and accident conditions.

10-year Goals
• Insert lead test rods into an operating commercial reactor
• Demonstrate non-intrusive technologies that enhance safety (e.g. instrumentation with enhanced accident tolerance)