Introduction to Nuclear Fuel Cycle and Advanced Nuclear Fuels

Jon Carmack
Deputy National Technical Director
Fuel Cycle Technology Advanced Fuels Program

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The Evolution of Nuclear Power

Generation I

Early Prototype Reactors

- Shippingport
- Dresden, Fermi I
- Magnox

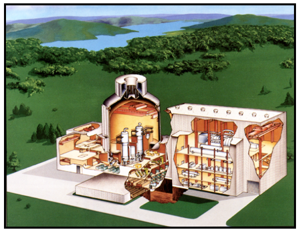
Generation II

Commercial Power Reactors

- LWR-PWR, BWR
- CANDU
- VVER/RBMK

Generation III

Advanced LWRs



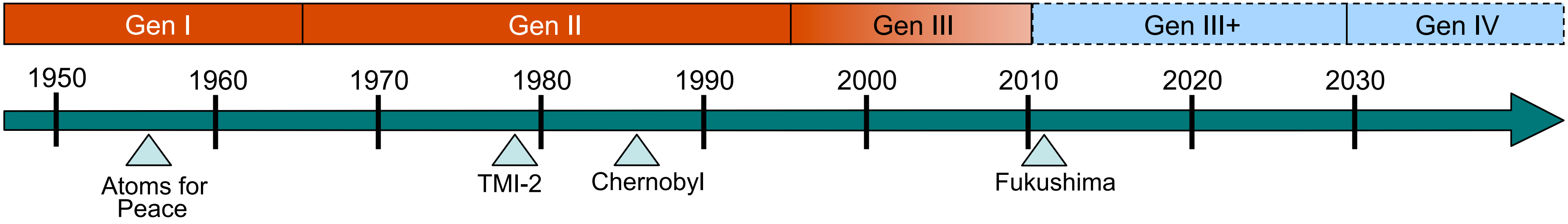
- ABWR
- System 80+
- AP00
- EPR

Near-Term Deployment

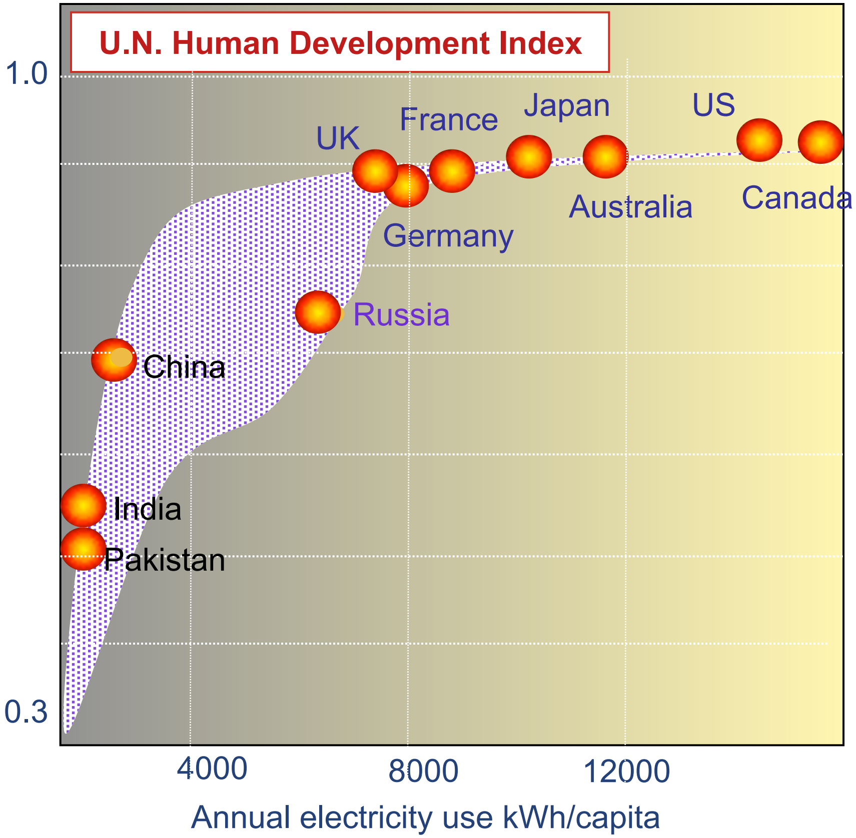
Generation III+ Evolutionary Designs Offering Improved Economics

Generation IV

- Highly Economical
- Enhanced Safety
- Minimal Waste
- Proliferation Resistant



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.

Vocabulary

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

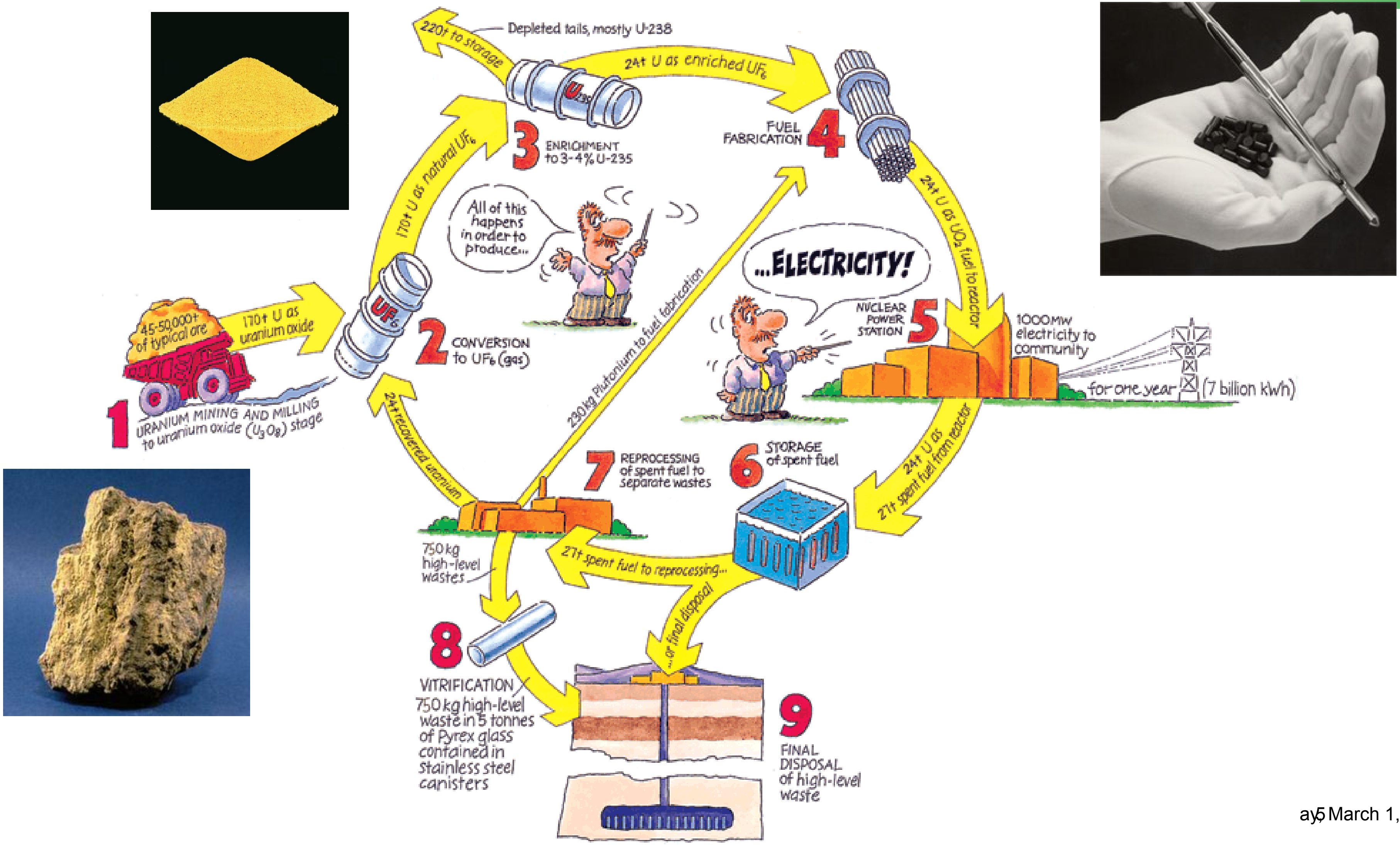
LWR – Light Water Reactor (primarily critical on thermal neutrons)

FR – Fast Reactor (primarily critical on fast neutrons, >1MeV)

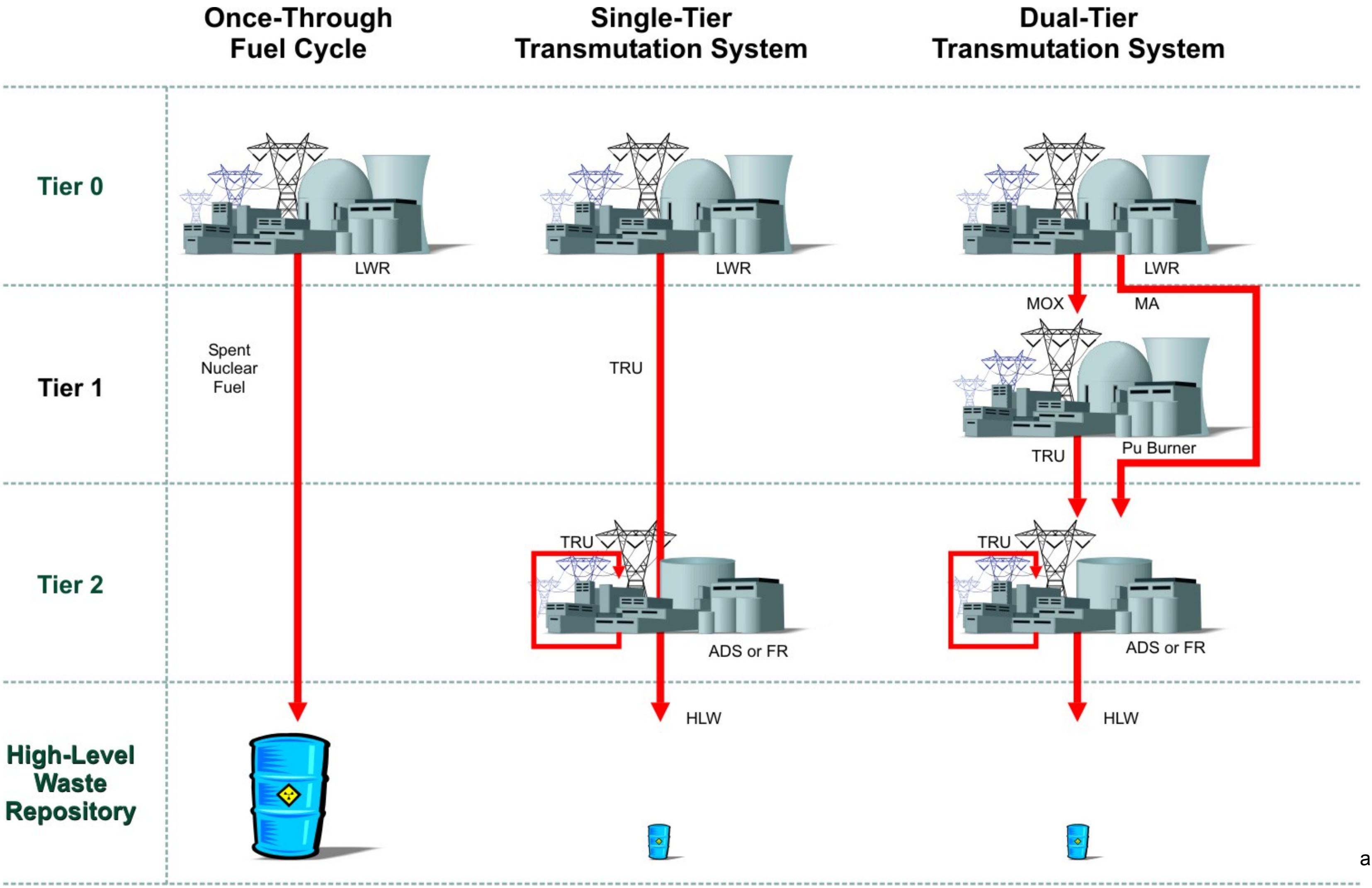
Spent Nuclear Fuel (SNF) – Fuel that can not be recycled

Used Nuclear Fuel – Fuel that can be recycled

The Nuclear Fuel Cycle



General Nuclear Fuel Cycle Concepts



Once-Through Fuel Cycle

Single-Tier Transmutation System

Dual-Tier Transmutation System

Tier 0

LWR

LWR

LWR

Tier 1

Spent Nuclear Fuel

TRU

MOX

MA

TRU

Pu Burner

Tier 2

TRU

ADS or FR

TRU

ADS or FR

High-Level Waste Repository

HLW

HLW

DOE Advanced Fuel Development

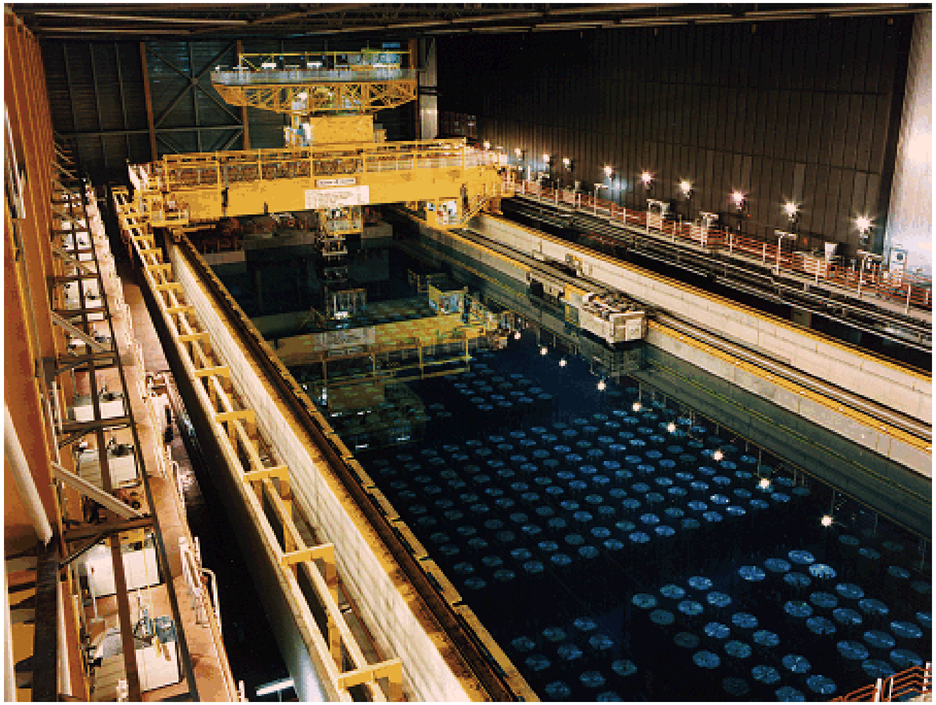
Campaign Mission: Development and demonstration of advanced fuels (and cladding) to support the sustainable nuclear energy and associated fuel cycles using a goal-oriented science based approach.

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?

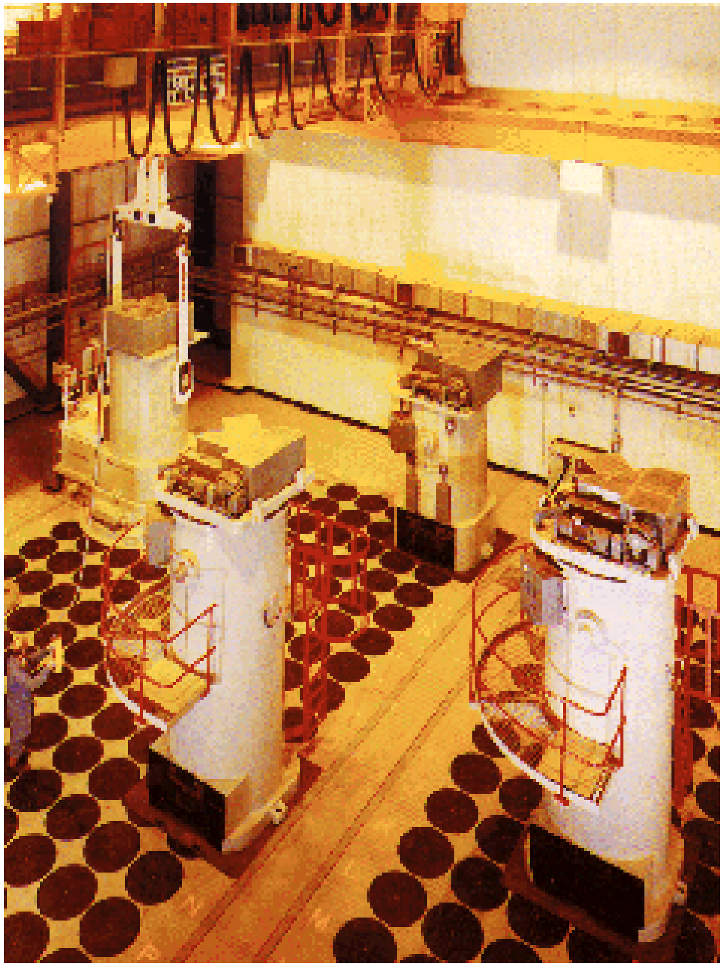


<10 years storage in a water pool

Dry and Transfer to Cask Storage

High Level Waste Disposal

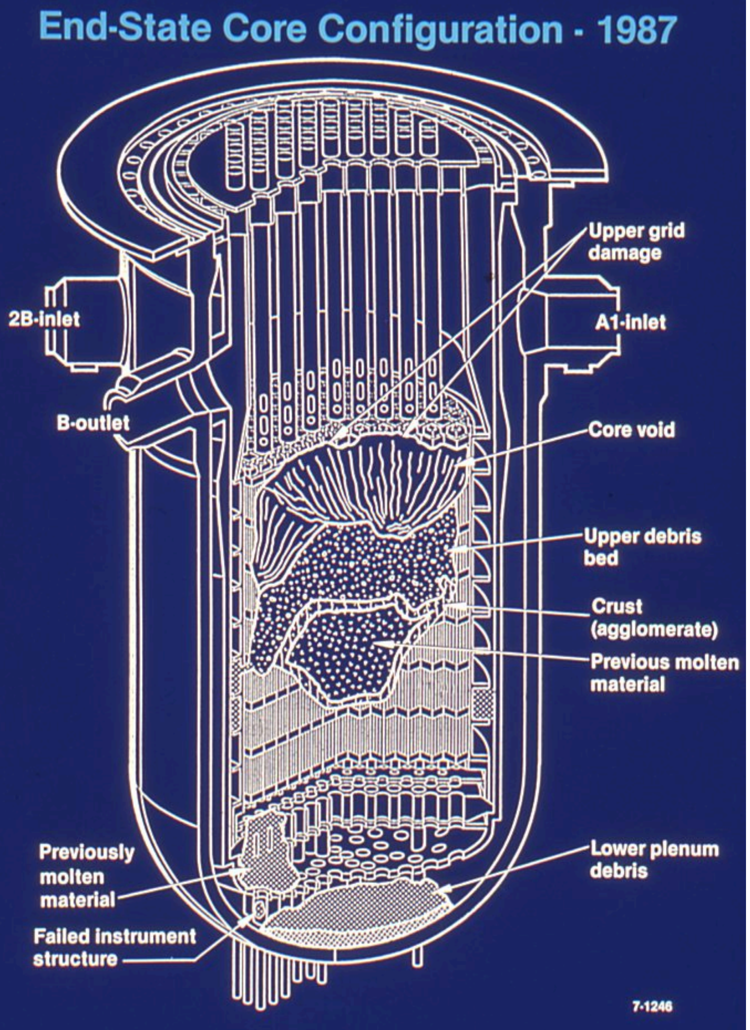
Vitrification - a long term storage option for the minor actinides.



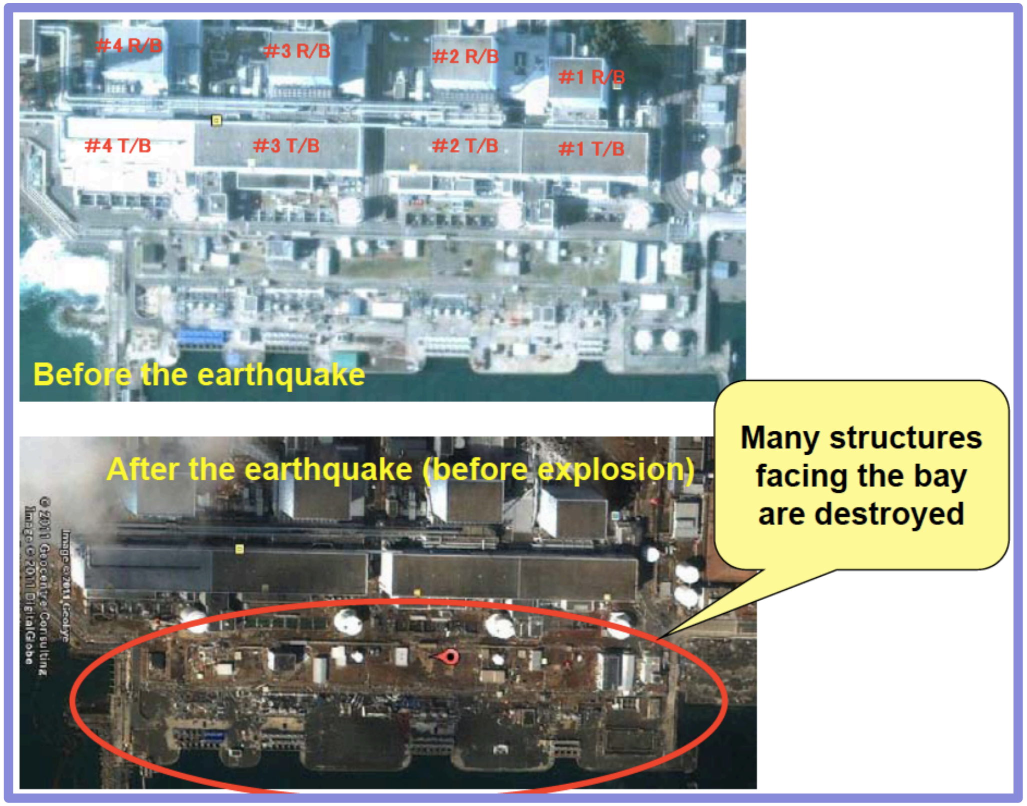
- Used in Europe for Fission Products and minor actinides resulting from reprocessing
- Used for weapons process waste at PNNL
- Recycle of Used Fuel extracting Pu for MOX
- Stored in an engineered facility

Enhanced Accident Tolerant Fuels for LWRs

1979 TMI-2 Loss of Cooling Accident

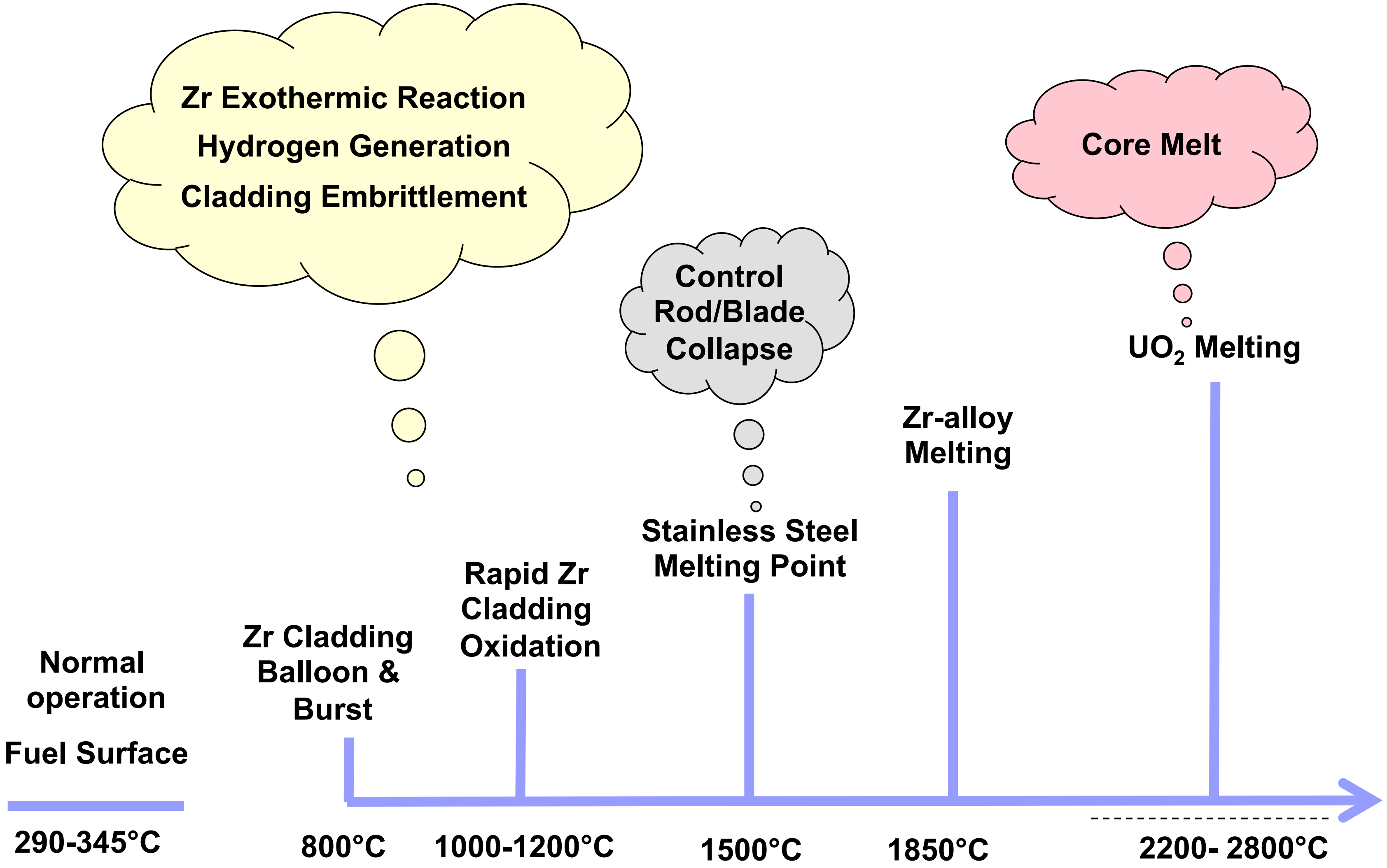


2011 Earthquake, Tsunami, and Station Blackout at Fukushima Dai-ichi NPS



Many structures facing the bay are destroyed

Fuel Behavior Under LOCAs (courtesy Bo Chang)



Zr Exothermic Reaction
Hydrogen Generation
Cladding Embrittlement

Control Rod/Blade Collapse

Core Melt

Normal operation
Fuel Surface
290-345°C

Zr Cladding Balloon & Burst
800°C

Rapid Zr Cladding Oxidation
1000-1200°C

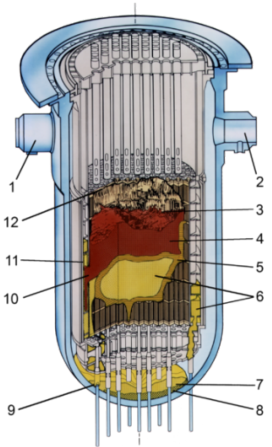
Stainless Steel Melting Point
1500°C

Zr-alloy Melting
1850°C

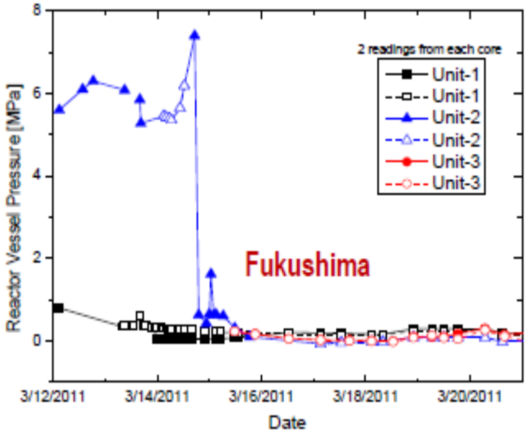
UO_2 Melting
2200- 2800°C

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



TMI-2 Core End-State Configuration (NRC)



- **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?

High temperature during loss of active cooling

Improved Reaction Kinetics with Steam

-Heat of oxidation
-Oxidation rate

Slower Hydrogen Generation Rate

-Hydrogen bubble
-Hydrogen explosion
-Hydrogen embrittlement of the clad

Improved Fuel Properties

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

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

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)*