U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Fuel Cycle Research and Development

Fuel Cycle Characteristics Affecting Performance

Temitope Taiwo
Department Manager
Argonne National Laboratory

Meeting on Nuclear Fuel Cycle Options
Argonne, IL, April 25, 2012

Presentations

1. Purpose and Objectives of the 2013 Evaluation and Screening Effort
   - Background
   - Context
   - Overall Process
2. **Fuel Cycle Characteristics Affecting Performance**
3. Approach for Development of Sets of Fuel Cycle Options and Groups
4. Examples of Fuel Cycle Options
5. Process for Submitting Fuel Cycle Concepts
   - Role of Participants
   - Requested information
   - Steps of the Process

Use of Basic Characteristics

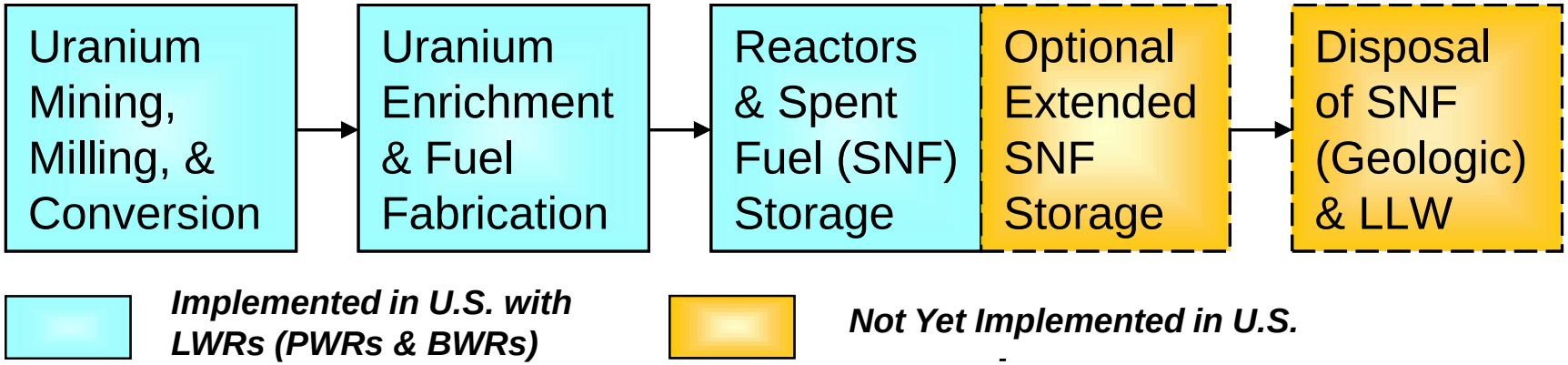
- **How does one ensure that a list of fuel cycle options is comprehensive for the evaluation and screening?**
  - Start with the underlying physics that determines how incoming materials are used and what products they will make
  - This approach is based on the recognition that many fuel cycle metrics are derived from nuclear material mass amount, nuclide content, etc for an option

Basic Characteristics

- **Once-through or Recycle (Limited or Continuous)**
- **Neutron irradiation system: reactor or externally-driven**
- **Choice of fuel materials**
- **Neutron spectrum: thermal, intermediate, or fast**
- **Need for uranium enrichment**
- **How fuel is treated following discharge from reactor**
  - Extended storage prior to disposal or reprocessing?
  - Processing for waste management purposes?
- **Content and characteristics of materials sent to geologic disposal and disposal environment**
- **Others**

Fuel Cycle Type: Once-Through

- **Nuclear fuel (Uranium and/or Thorium) is used once in fuel cycle**
- **Spent nuclear fuel (SNF) is disposed in a geologic repository**

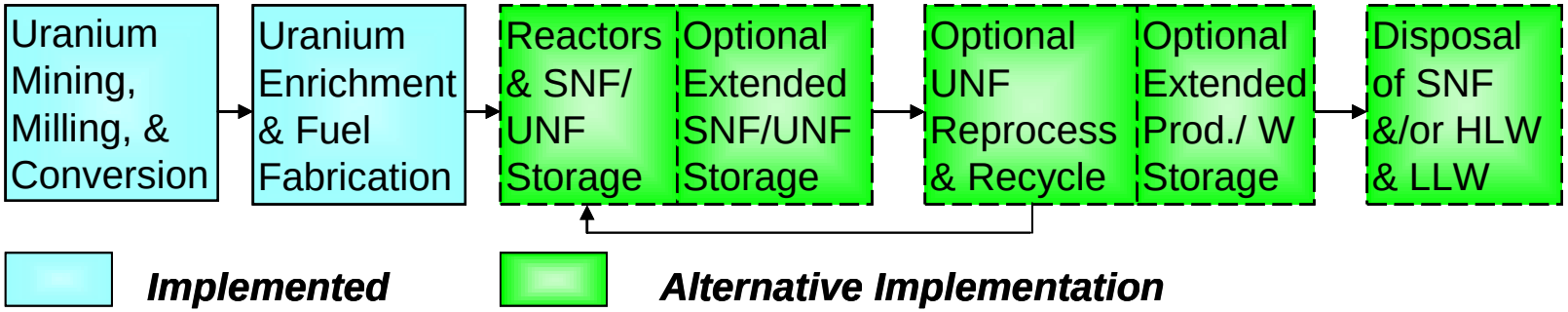


SNF considered as waste

- **Evaluation and screening of fuel cycle options will also include the option of limited "processing" for waste management purposes prior to disposal**

Fuel Cycle Type: Limited Recycle

- **Used nuclear fuel is reprocessed and fuel material is recycled once or a few times**
- **High level waste (HLW) is sent to a repository in addition to spent fuel; low level waste (LLW) is disposed**
- **Various concepts have been proposed for limited processing of used and spent fuels**

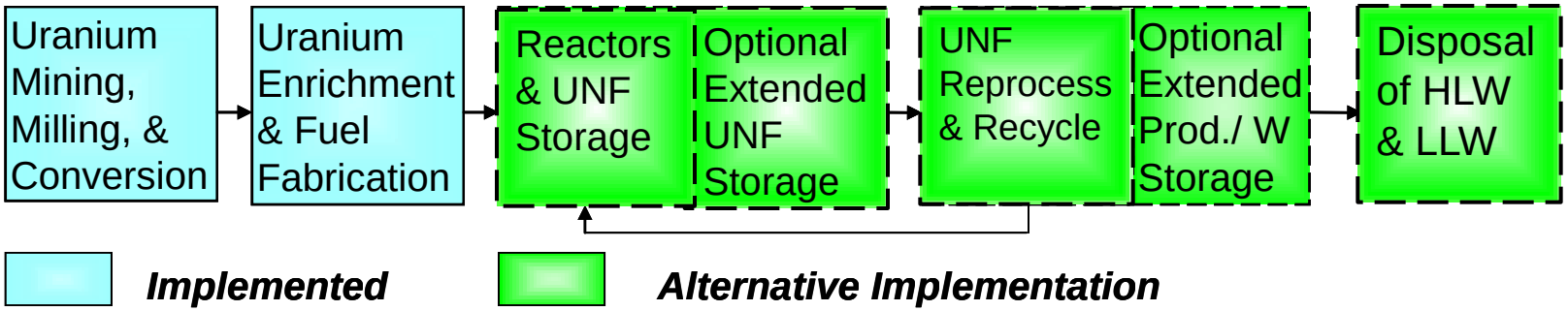


SNF considered as waste
UNF considered as a resource

Limited recycle system with uranium option shown

Fuel Cycle Type: Continuous Recycle

- **Used nuclear fuel is reprocessed after use and fuel material recycled on a continuing basis**
- **Following reprocessing, only HLW, not SNF, is disposed in a geologic repository; LLW goes to disposal**



UNF considered as a resource

Option with uranium fuel shown

Neutron Irradiation System

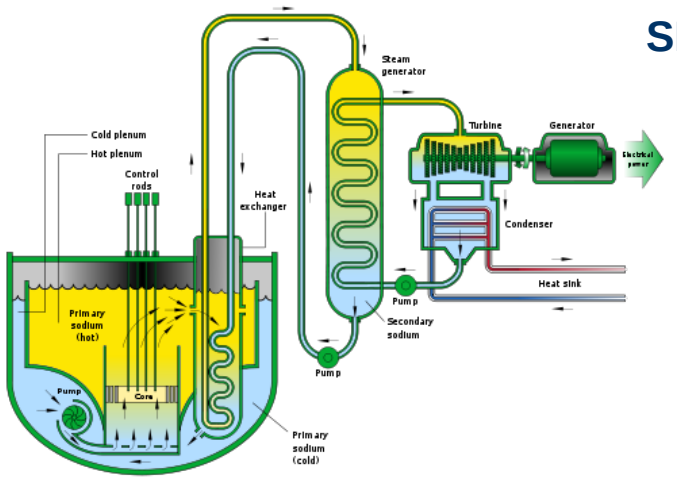
Evaluation and Screening effort will focus on two neutron irradiation systems

- **Reactor systems**
  - Can sustain a fission chain reaction for fuel irradiation and utilization
- **Externally-driven subcritical systems (EDS)**
  - Requires external device for extra neutron source to maintain a constant power (reaction rate) level in the irradiation system
  - Allows alternative approach for using fertile fuel and higher actinides

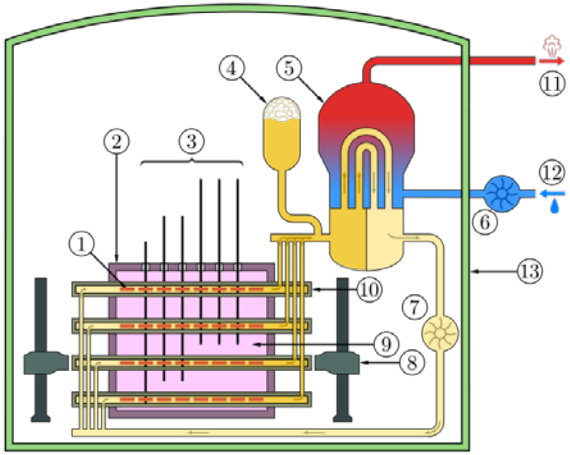
Neutron Irradiation System (Cont'd)

Examples of Reactor Systems Considered

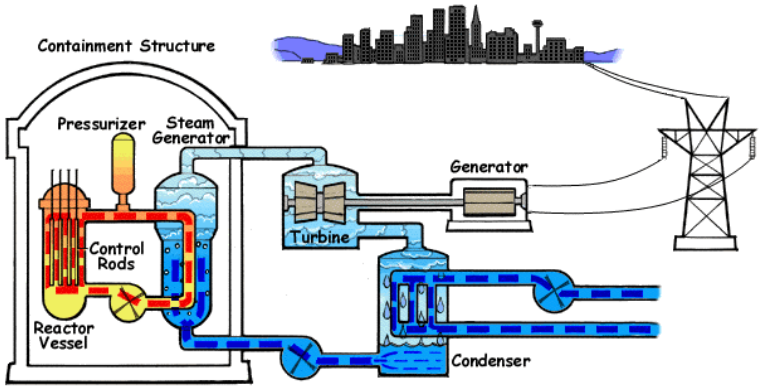
- Currently operating reactors such as LWRs, CANDU, and AGR
- Advanced reactors (such as the Gen IV systems, SFR, LFR, GFR, VHTR, SCWR, MSR)



SFR



CANDU

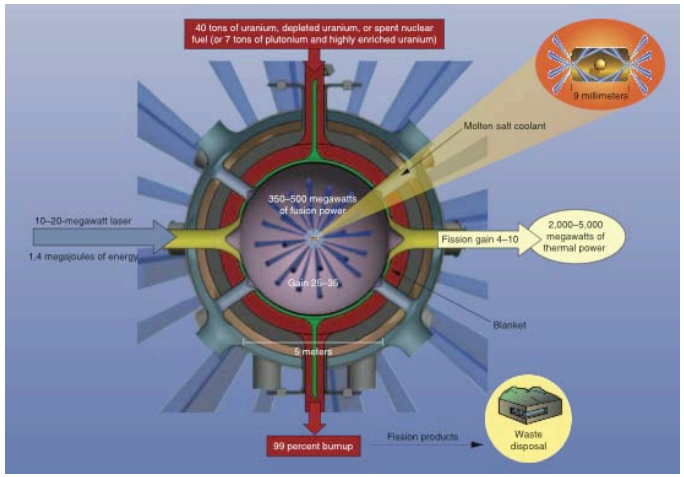


PWR

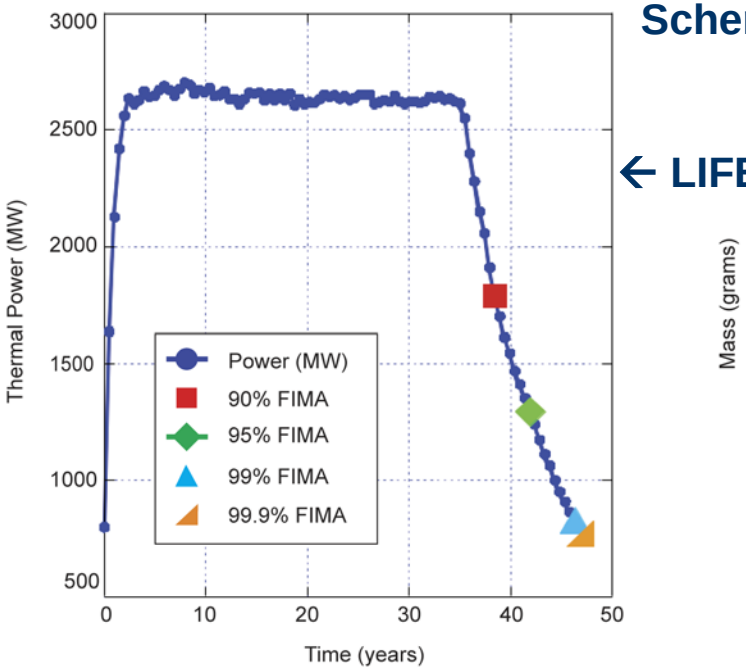
Neutron Irradiation System (Cont'd)

- **Examples of externally-driven subcritical systems**
  - Accelerator-driven system (ADS)
  - Fusion-fission hybrid (FFH) device

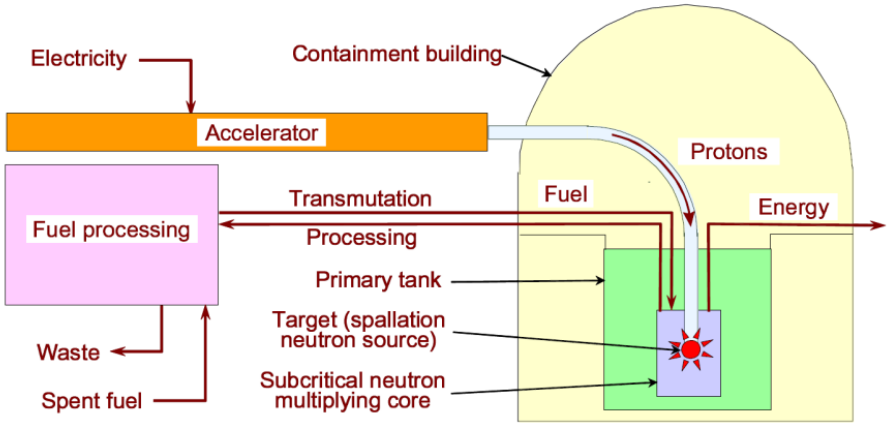
Schematic of LIFE →



← LIFE Power Profile



Mass (grams)



Schematic of ADS

Fuel Material

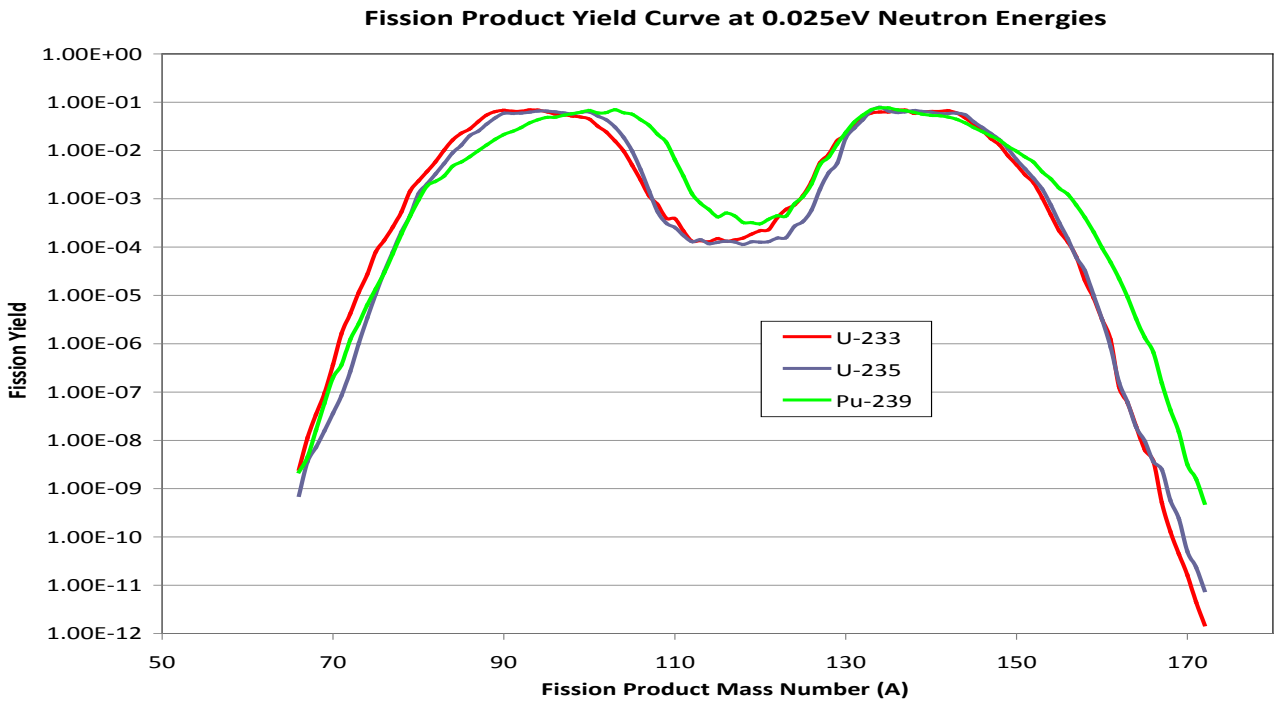
- **Two naturally occurring sources of nuclear fuel**
  - Uranium: primarily consists of a fissile isotope (Uranium-235) and a fertile isotope (Uranium-238)
  - Thorium: only a fertile nuclide, Thorium-232 (Th-232)
- **Fissile material is required in order to produce nuclear power**
- **Natural or enriched Uranium can be used to fuel a reactor system**
  - Since Thorium has no fissile isotope it must be used with fissile material in reactor systems
- **Thorium-only fuel can be used in an EDS, but fissile material must first be produced in that system**
  - Externally-produced neutrons are used for converting Thorium-232 into U-233 (which is a fissile material)

Fuel Material (Cont'd)

- **Characteristics of the irradiation system and choices of materials used in irradiation determine the product materials (UNF/SNF)**
  - Choice of fissile material(s): U-235, Pu-239, U-233
  - Choice of fertile material(s): U-238, Th-232, etc.
- **Material choices affect yield of fission and activation products**
- **Use of thorium will result in a reduced production of higher actinides, but greater production of other isotopes**

Fuel Material (Cont'd)

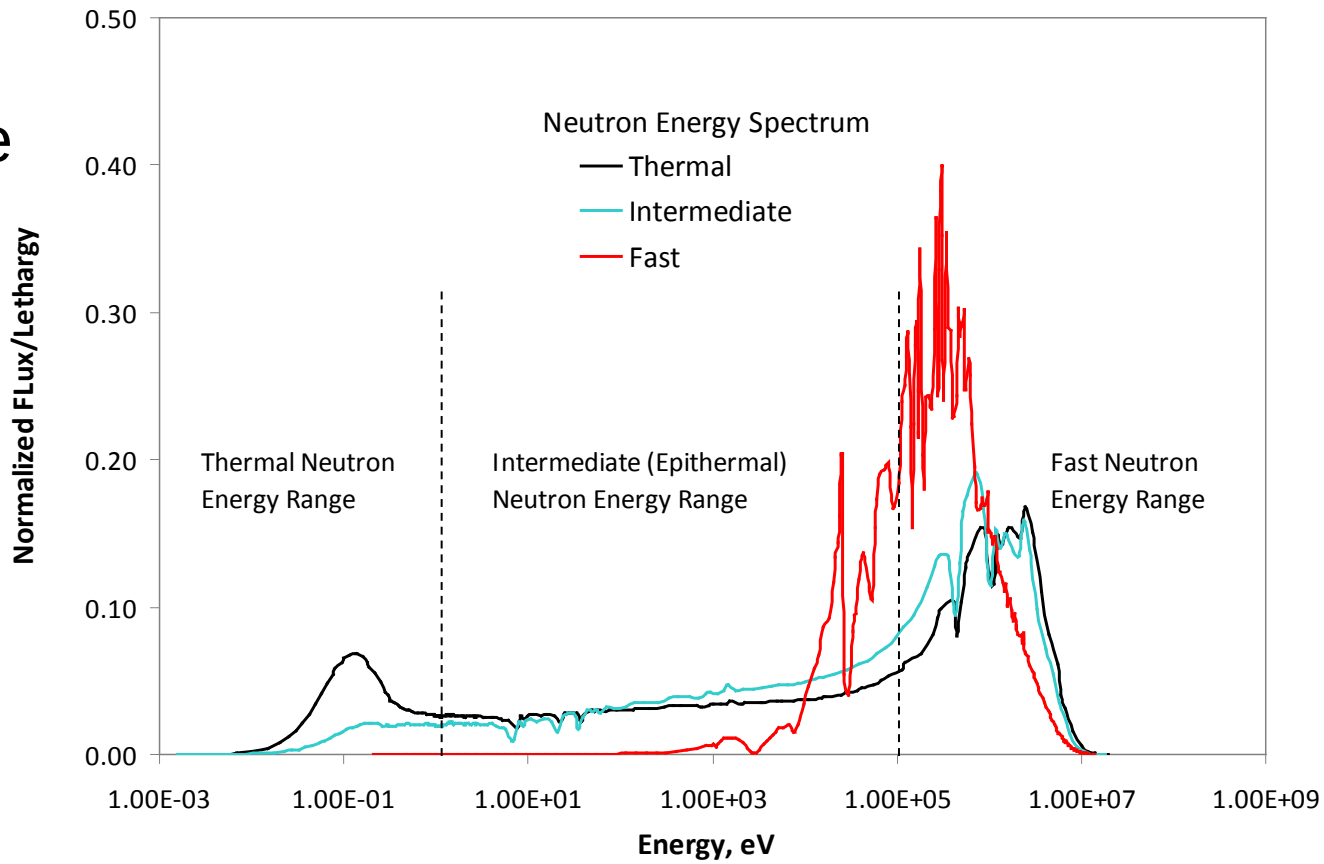
- **Distribution of the yield of fission products depends on fissile material in fuel**
  - Affects amount of each fission product in spent fuel



Neutron Spectrum

- **Neutron Spectrum categories:**
  - Thermal
  - Intermediate
  - Fast

Neutrons from fission are born in the high (fast) energy range and have to be slowed down for interaction at lower energies



Neutron Spectrum (Cont'd)

- **Neutron spectrum affects neutron balance and system ability to sustain fission chain reaction or reaction rate level**

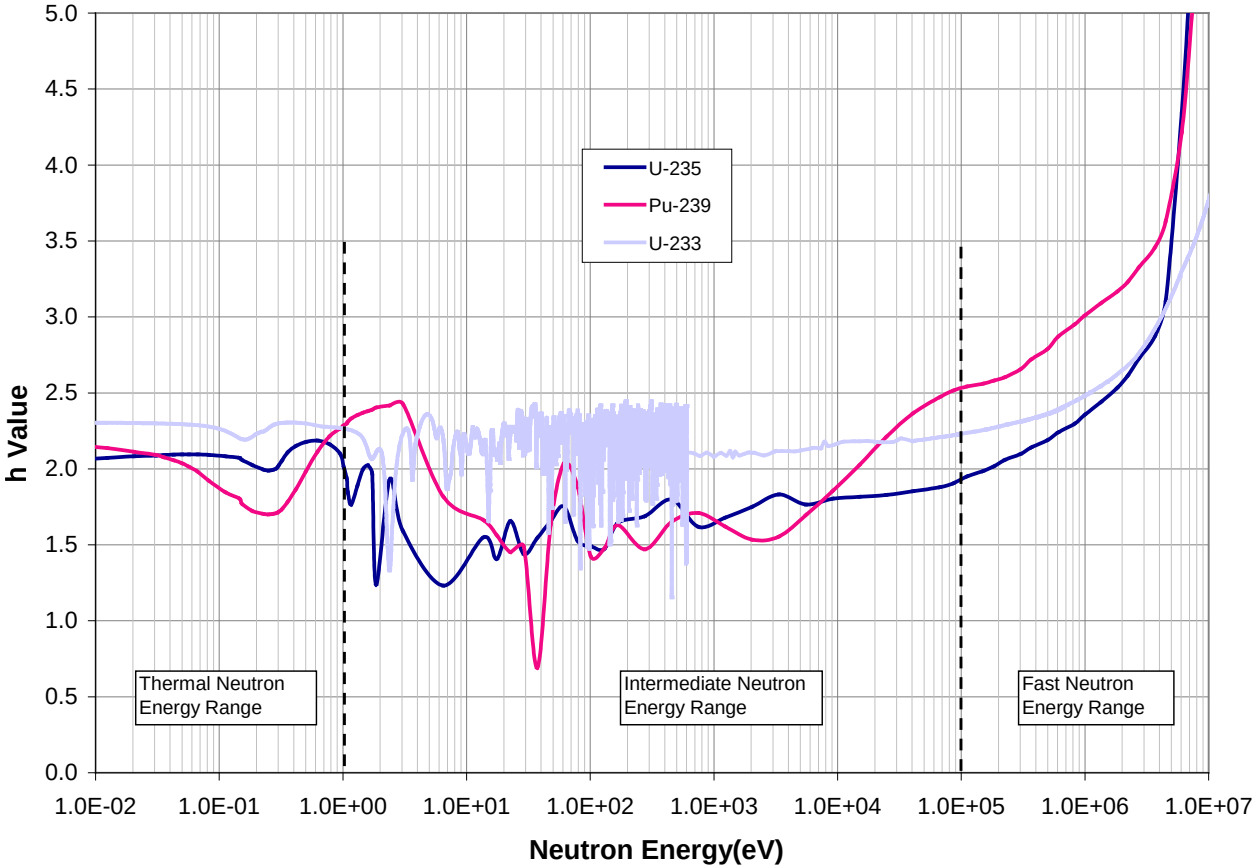
Eta (η) is the number of fission neutrons produced per absorption

An η value greater than 1 is required for (critical) nuclear reactors (due to neutron losses)

Irradiation system with $\eta > 1$ is required for critical converter system

$\eta > 2$ is required for breakeven and breeder systems

Breeding is possible in both thermal and fast spectra



Neutron Spectrum (Cont'd): Burner, Breakeven and Breeding

$$^{238}\mathrm{U}(n,\gamma)\,^{239}\mathrm{U} \xrightarrow[23.5\ \mathrm{m}]{\beta^-} {}^{239}\mathrm{Np} \xrightarrow[2.35\ \mathrm{d}]{\beta^-} {}^{239}\mathrm{Pu}$$

$$^{232}\mathrm{Th}(n,\gamma)\,^{233}\mathrm{Th} \xrightarrow[22.2\ \mathrm{m}]{\beta^-} {}^{233}\mathrm{Pa} \xrightarrow[27.4\ \mathrm{d}]{\beta^-} {}^{233}\mathrm{U}$$

- **Conversion process is quantitatively described in terms of the conversion ratio CR**
  - Defined as the average number of fissile atoms produced in a reactor per fissile atom consumed
- **For breeding, η must be substantially greater than 2**
  - One fission neutron must eventually be absorbed in fuel to keep the chain reaction critical
  - More than one neutron must be absorbed in fertile material to produce fissile material
- **Systems: CR < 1 burner; CR ~ 1 breakeven; and CR > 1 breeder**

Neutron Spectrum (Cont'd)

Breakeven and breeder irradiation systems are possible with either thermal or fast spectra

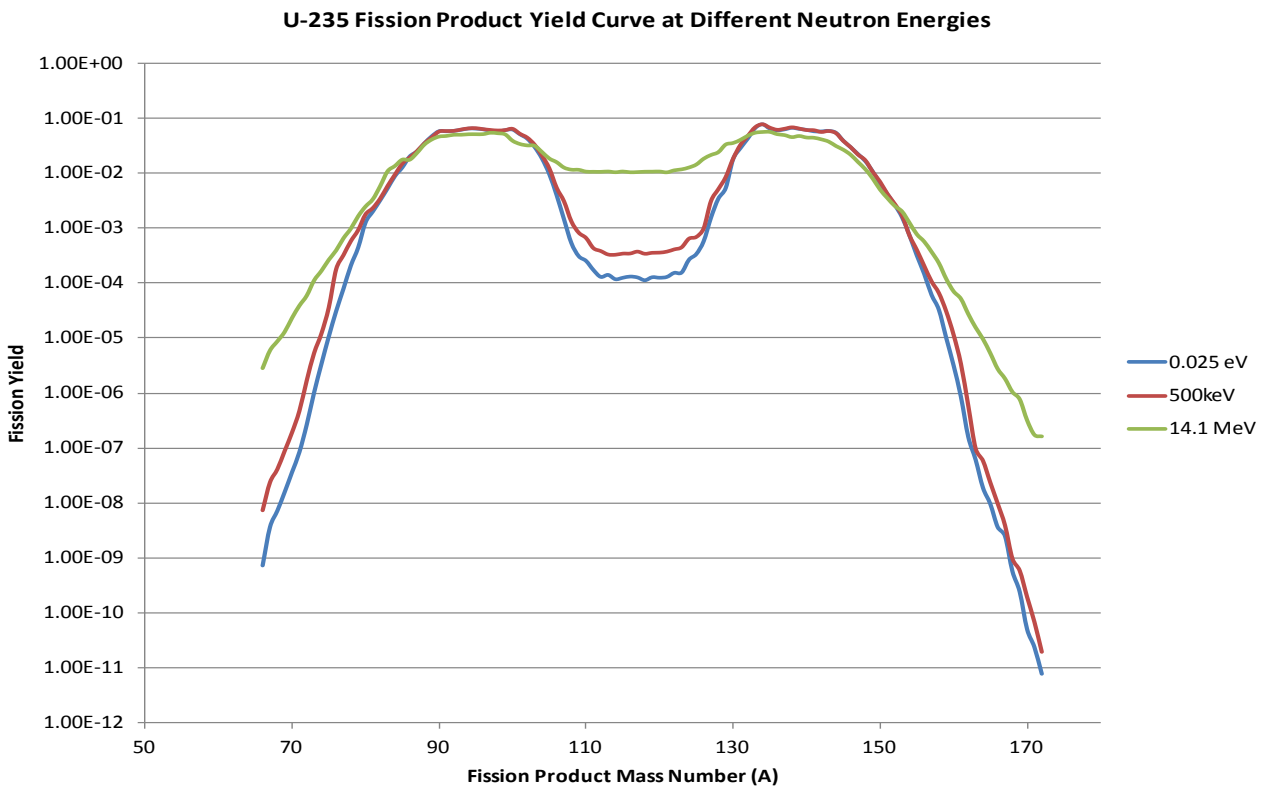
- **In the thermal energy range, U-233 η-value is sufficiently greater than 2 and allows breakeven or breeding of fissile material in Th/U-233 fueled systems**
  - Thermal-spectrum reactors in which breeding is possible include molten salt reactors and water-cooled reactors (demonstrated during the Shippingport light-water breeder experiment)
  - Designs minimize neutron losses arising from neutron absorption
- **Fast spectrum systems are more effective breeders when using U/Pu fuel**
  - Very high breeding ratio (>1.5) reactor design is possible

Neutron Spectrum (Cont'd)

- **Ratio of fission-to-capture is spectrum dependent and affects whether a nuclide preferentially fissions or undergoes successive captures to create heavier isotopes**
  - Affects the relative buildup of higher actinides in one system versus another

Neutron Spectrum (Cont'd)

- **Distribution of the yield of fission products is affected by neutron spectrum**



Uranium Enrichment

- **Whether uranium enrichment is needed depends on the fuel materials, neutron spectrum, and core design**
- **Neutrons must be slowed down to thermal energies and neutron losses and absorption must be minimized to not require fuel enrichment; e.g. in CANDU reactors**
- **Generally, enrichment requirement is lower for thermal spectrum systems than fast spectrum systems because of lower probability of neutron absorption in fertile isotope to fission in fissile isotope**
  - Enrichment requirement can be significantly reduced in fast spectrum systems by minimizing neutron leakage and breeding fissile material; e.g. as in breed and burn fast spectrum systems or traditional fast breeder reactors
- **Enriched uranium fuel is not required in equilibrium cycle of a breakeven or breeder reactor**
  - Breeding of fissile material can be used to displace uranium enrichment

Fuel Storage Duration and Processing

- **Extended storage prior to disposal or reprocessing?**
  - Decay product(s) might affect overall system performance (including irradiation, separations, fuel fabrication, and disposal subsystems)
- **Processing for waste management purposes without recycling?**
  - Can waste management be favorably affected by segregation of spent fuel content?
- **Reprocessing for recycle?**
  - Is it better to recycle some material by separations than direct disposal of spent fuel?

Disposal

- **Content and characteristics of nuclear materials sent to geologic disposal and the disposal environment can affect performance**
- **Spent fuel is a compact form for disposal**
  - Processing can alter the form(s) for storage and disposal
- **HLW can be designed to contain a subset of spent fuel contents, e.g., only those requiring geologic isolation**
  - For a recycle option, separations determines carryover of recycled elements into wastes
- **Many disposal environments are possible in principle, with differing abilities for isolating each element**

Other Characteristics

- **Thermal efficiency affects performance per GWe**
  - For example: Normalized per GWe, same spent fuel amount is reduced by as much as 50%, using VHTR instead of PWR
- **Use of more than one irradiation systems (e.g., EDS following a LWRs)**
  - Flexibility in design can help in meeting system goals