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Fuel Cycle Research and Development

Modified Open Fuel Cycle Systems and Potential Nuclear Data Needs

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Overview

- Background on Three Fuel Cycle Categories
- Examples of Systems in Three Fuel Cycle Categories
- Sample Impact of Systems on Nuclear Data Needs
- Conclusions

Three Fuel Cycle Categories in USDOE-NE Roadmap

- **Three fuel cycle categories**
  - Once-through
  - Modified open
  - Full recycle
- **Categories used to classify and differentiate fuel cycle nuclear systems**
- **Necessary for identifying areas of future R&D efforts**

Once-Through Fuel Cycle

- **U.S. currently utilizes the once-through fuel cycle in its commercial nuclear power sector**
  - Low enriched uranium (LEU) nuclear fuels are loaded into light-water reactors (LWRs) for purpose of power generation
  - Used nuclear fuel (UNF) removed following fuel utilization and stored prior to long-term disposal
  - Plants have high capacity factors (greater than 90%) and most likely will be around for balance of the century and beyond
- **Plan for UNF management is currently undefined**
  - Now domain of *Blue Ribbon Commission on America's Nuclear Future*

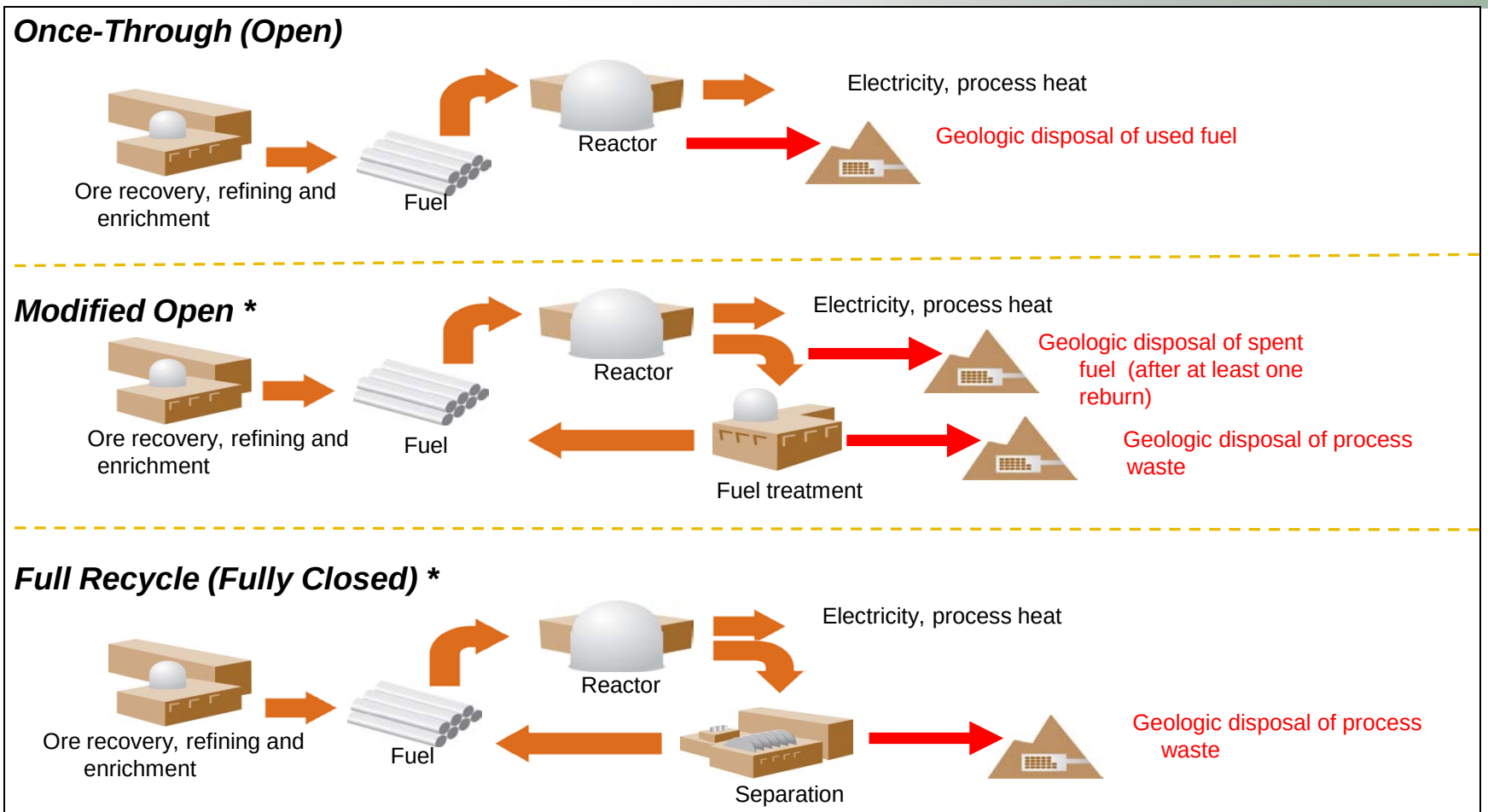
Full Recycle

- **Since advent of nuclear era, it has been anticipated that used fuel material could be processed and <u>fully recycled</u> with intent to better utilize nuclear fuel resources**
- **Uranium exploration with additional finds has alleviated urgency for a closed fuel cycle**
  - Proliferation risk considerations have been basis for some opposition to full recycle in the U.S.
- **Recycling of nuclear fuel has been considered for managing UNF within USDOE advanced nuclear fuel cycle programs in last few years**
  - ATW, AAA, AFCI, GNEP

Modified Open Fuel Cycle

- **<u>M. Crozat, April 2010 – Definition</u>: No or limited separations steps and processing applied to used fuel to extract more energy**
  - ***Spent*** fuel and high-level waste disposed instead of ***used*** fuel
- **Alternatively, a <u>modified open</u> cycle can be considered as a nuclear power approach in which fresh uranium, or thorium, or recovered fuel is used to generate power, and then is removed from the reactor with the back-end option of being stored in a repository or re-used at least once to generate additional power**
  - Modification or treatment of fuel between uses may be required
  - Used nuclear fuel (spent fuel) is discarded at some point in the fuel cycle when further re-use is not desirable or possible

Three Potential Fuel Cycle Options



*A specific fuel cycle strategy may include more than one fuel design, reactor design, or fuel treatment process.

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Examples of Nuclear Systems in Three Fuel Cycle Categories

Once-Through	Modified Open	Full Recycle
Light water reactors (LWRs)	Limited LWR/MOX recycle	Molten salt system with U/TRU or U/Pu closed cycle
Advanced LWRs (ALWRs)	Limited LWR/IMF recycle	Fast Spectrum System with U/ TRU or U/Pu closed cycle
Heavy-Water reactors (HWRs)	LWR/ Thorium use/recycle	LWR Th/U-233 closed cycle
Gas-cooled, graphite moderated reactors (including the high temperature reactors (HTRs))	Breed and burn concepts with fuel reconditioning	Thermal reactor multirecycle with fissile material support (including LWRs, HTRs using MOX fuel and IMF)
Breed and burn concepts (including Traveling wave reactor concept) without reprocessing		Double-tier thermal/fast spectrum systems
	Deep-burnup concept in gas-cooled thermal reactors	
	Molten salt system with limited on-line processing	
Fusion-fission hybrids		
Acceleration-driven systems		

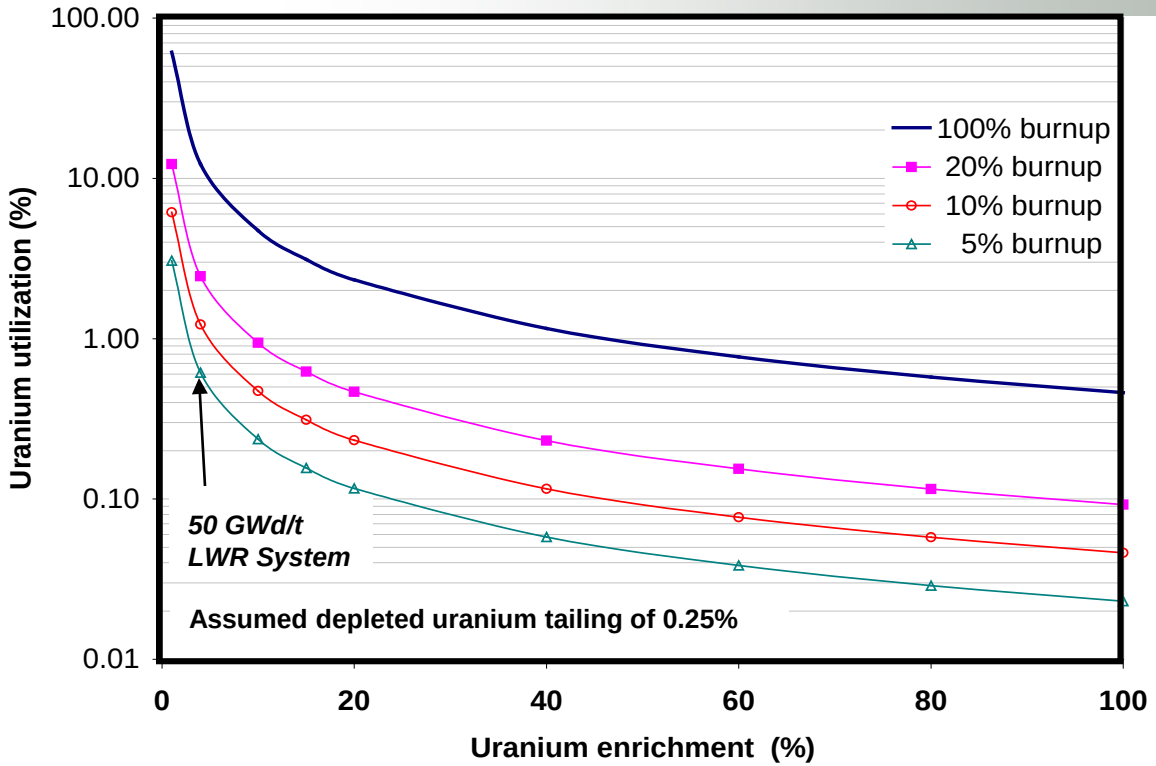
- Members of categories evolving; e.g. HWRs and HTRs now classified as Once-Through
- Does Full Recycle systems have to utilize all TRU in the fuel cycle or Pu-only acceptable?
- Observation: Class and specific metric could dictate answer obtained; e.g. MOX-Pu fuel near-term implementation

Once-Through Fuel Cycle Nuclear Systems

Estimated Uranium and U-235 and U-238 Utilizations in PWRs and VHTR

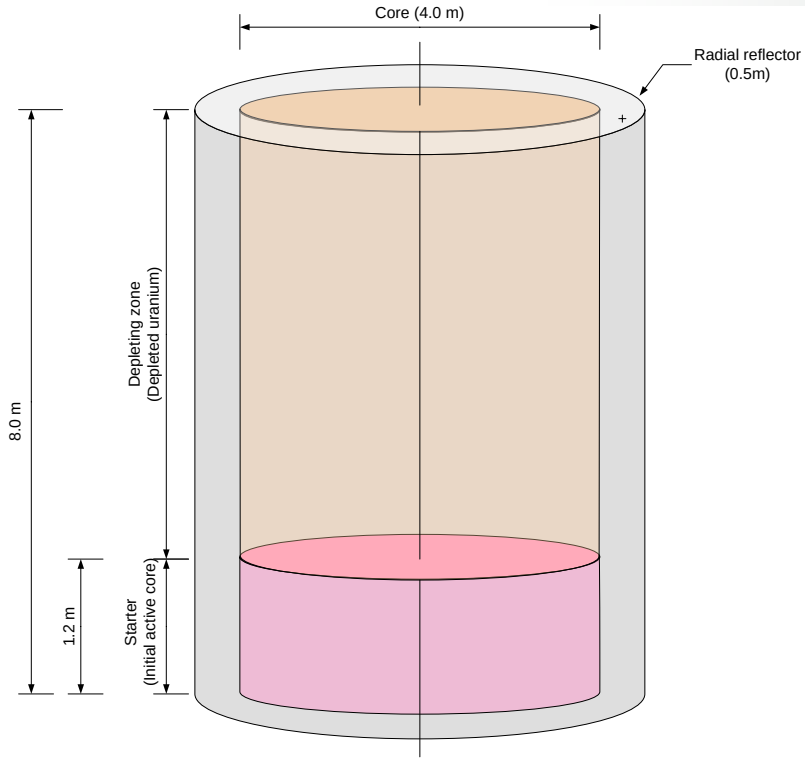
Parameters	PWR-UOX 50 GWd/t	PWR-UOX 100 GWd/t	VHTR 100 GWd/t
Enrichment, %	4.2	8.5	14.0
Mass ratio of required natural uranium to enriched uranium	8.6	17.9	29.9
Uranium utilization, %	0.60	0.57	0.35
Percent of heavy metal (HM) that fissions, % (i.e., burnup)	5	10	10.5
U-235 utilization in fuel, % (i.e. U-235 in fuel that fissions)	69	70	52
U-238 utilization in fuel, % (i.e. U-238 in fuel that fissions)	2.4	4.8	3.7
Fission power contribution from U-238 or its conversion, %	44	42	30

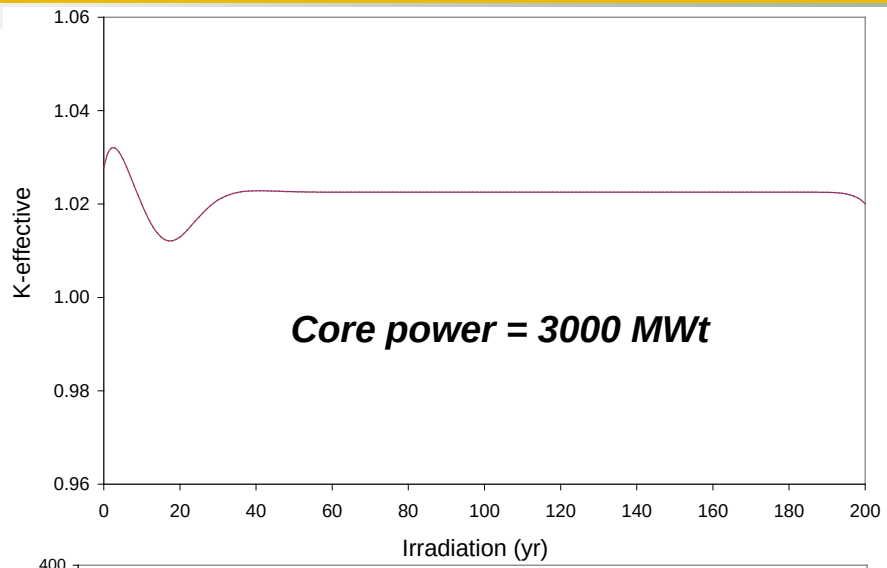
Uranium Utilization as Function of Uranium Enrichment and Burnup

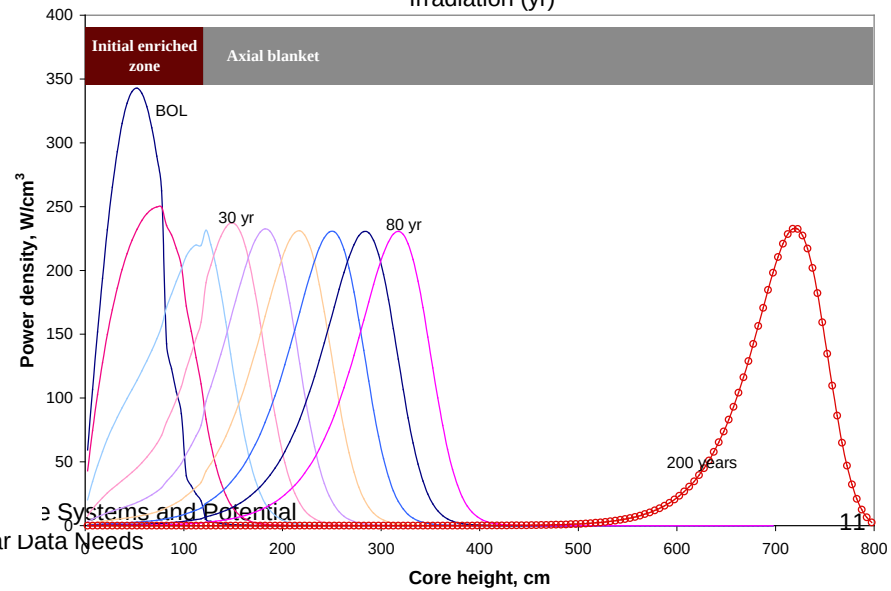


- **Low enrichment and high fuel burnup is favorable for high uranium utilization**
- **Physics limits and practicality issues affect achievable uranium utilization at low uranium enrichment**
- **To get high uranium utilization, tails must be re-used**

CANDLE – Axial Burn-zone Propagation w/o Fuel Movement

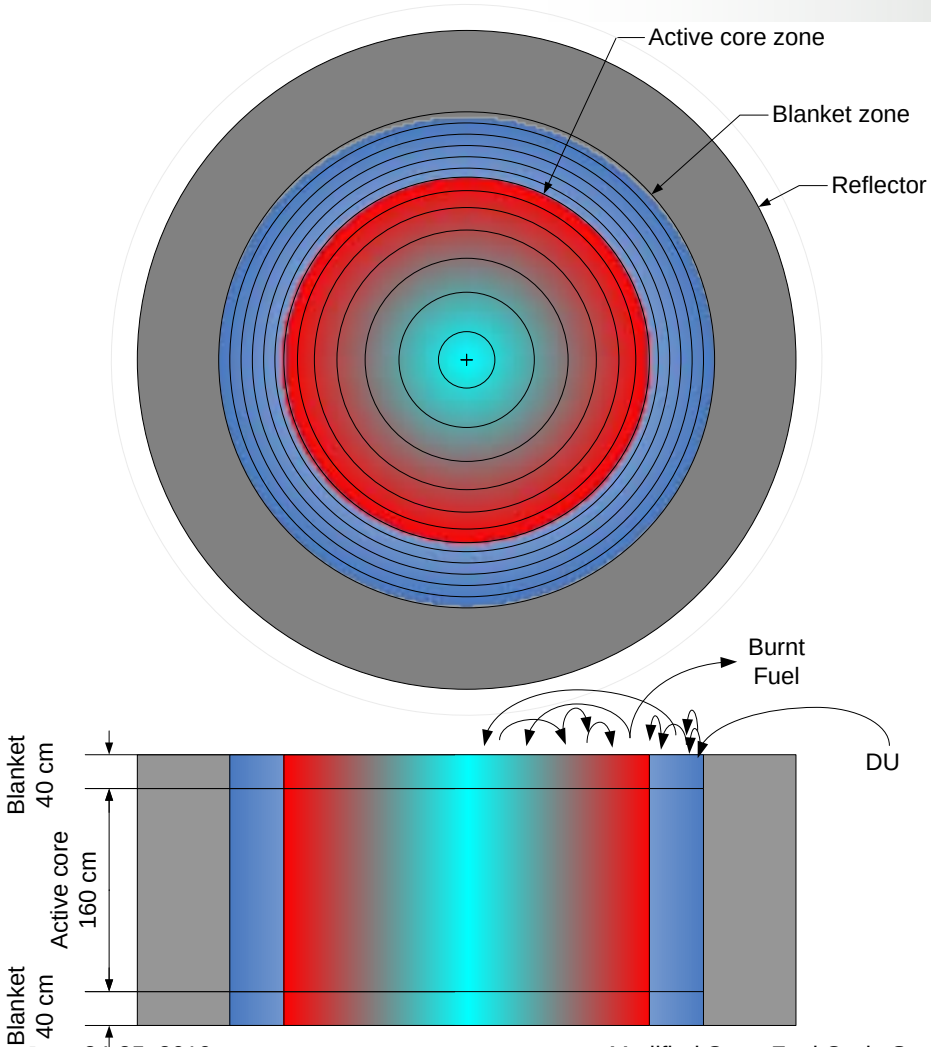






- **High fuel burnup, flux and neutron leakage into blanket required for propagation**
- **Large depleted uranium loading required**
- **Long core life needed**
- **Uranium utilization as high as 30%**

Feasibility Study of Radial Shuffling without Recycling



- **Thermal power = 3000 MWt**
- **Core configuration**
  - Number of assemblies = 408
  - Active core
    - *Height = 1.6 m*
    - *Diameter = 3.3 m*
  - Blanket thickness
    - *Radial = 0.5 m*
    - *Axial = 0.4 m*
  - Fuel volume fraction = 40%
  - Initial core enrichment = 9.2%
- **Fuel management scheme**
  - 34-batch and 1.5-yr cycle length
  - DU is fed to radial blanket, resides for 21 years, and shuffled to active core
  - Fuel resides in active core for 30 years and discharged

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Notional Practical Limits on Uranium Utilization and Burnup for Fuel Cycle Categories

Fuel Cycle Category	Uranium Utilization (%)	Burnup (%)
Once-Through		
LWRs/ALWR	<0.7	<10
Modified Open Fuel Cycle		
Modified thermal systems	<1	<10
Once-through fast spectrum reactors	<1.5	<20
Propagation burn-zone cores, no reconditioning	<5-10	<5-10
Propagation burn-zone cores, with reconditioning	<20-50	<20-50
Subcritical systems, no reconditioning	<10-20	<10-20
Subcritical systems with reconditioning or reprocessing	~99	20 or 99*
Full Recycle		
Symbiotic LWR-FR (CR < 1.0)	<1.5	<20%
Fast reactor (CR > 1.0)	>95%	<20%

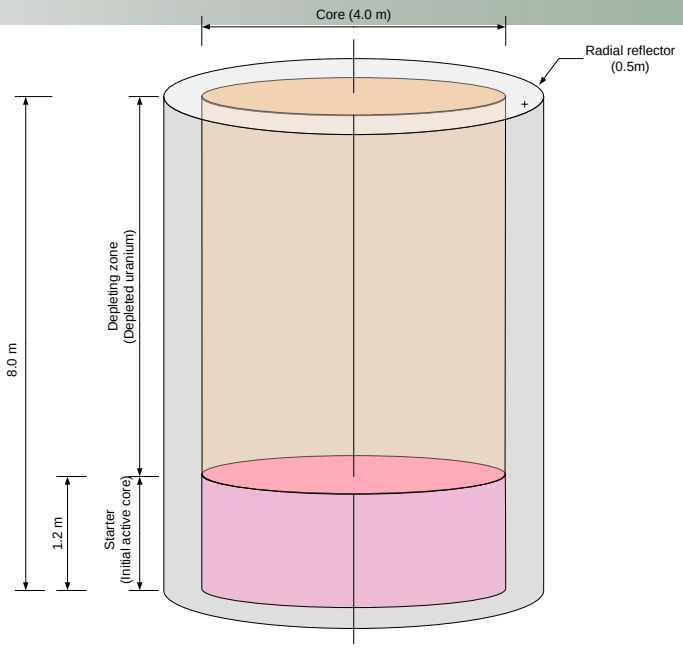
*Depends on if reconditioning is considered full recycle or not. If full recycle, then the lower limit applies.

Design Issues with High Uranium Utilization Systems

- **Time required for fissile material (Pu or U-233) buildup**
- **Long core life greater than reactor life required for high U utilization**
- **High fuel burnup required to attain high uranium utilization**
  - High fluence-to-burnup ratio could be limiting to burnup and advanced fuels needed
- **For systems advocating simplified recycling (e.g., melt refining), the fuel cycle implications of such approaches need to be quantified**
  - Are there better ways to achieve goal?
- **Very large core dimensions might not yield an economic system**
- **Axial burn-zone propagation core**
  - Other issues: reactivity control, high pressure drop, and “active” core cooling
- **Radial burn-zone propagation core**
  - Other issues: Adequate core cooling (advanced orificing), whole core shuffling, and power peak control
- **For one-pass systems: issues with spent fuel, including Pu content**
- **Non-proliferation advantage is main attraction, but difficult to quantify**

Calculation Tools/Approach – Sensitivity and Uncertainty Evaluation

- **Cross sections generated with the MC^2-2 code and ENDF/B-V nuclear data in 21 energy groups**
- **Forward and adjoint fluxes calculated with DIF3D finite difference diffusion theory option**
- **Burnup calculations performed with REBUS-3**
- **Sensitivity coefficient calculations done with diffusion theory option in VARI3D**
- **Parameter uncertainties estimated using BOLNA covariance matrix by collapsing the sensitivity coefficients into the 15 energy group structure used for the covariance data**



- Starter divided into 3 zones axially to enhance power propagation; with U-enrichments of 13, 7 and 3%, for axial zones of 80, 20, and 20 cm from bottom
- Depleted uranium (0.3%) is blanket and radial reflector

k_{eff} Uncertainties – BOLNA Data

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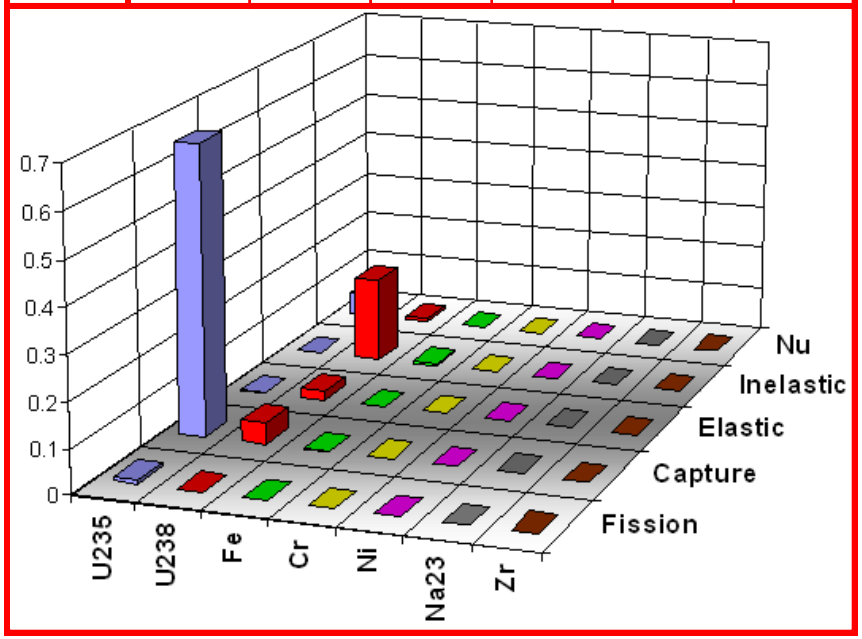
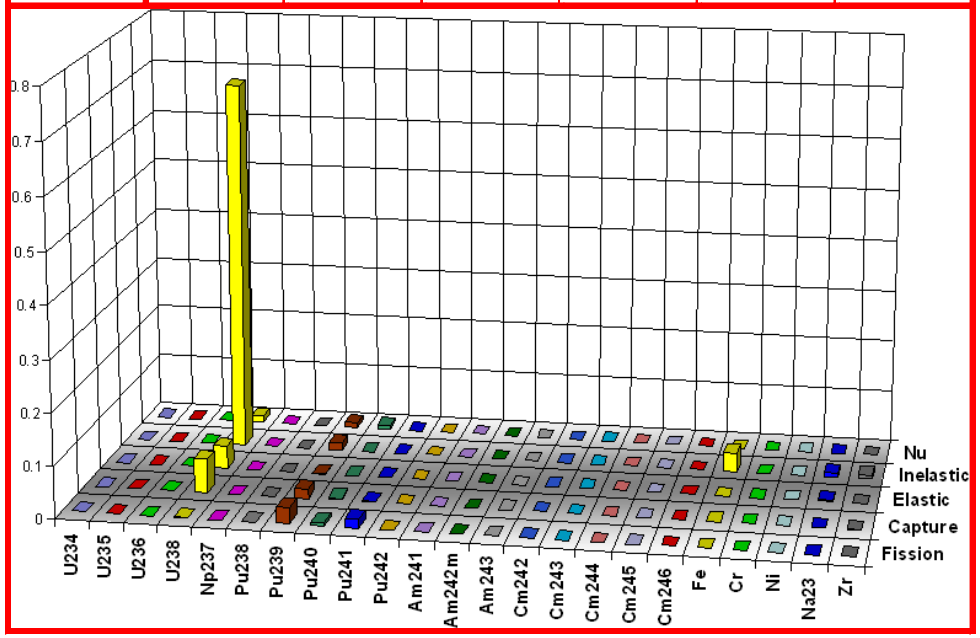
Uncertainty Breakdown (%) for BOC Multiplication Factor

Isotope	Fission	Capture	Elastic	Inelastic	Nu	Total
U235	0.22	1.70	0.10	0.04	0.48	**1.79**
U238	0.06	0.47	0.31	0.92	0.20	**1.10**
Fe		0.05	0.02	0.17		**0.18**
Cr		0.01	0.01	0.01		**0.02**
Na23			0.01	0.05		**0.05**
Zr		0.02	0.03	0.10		**0.11**
Total	**0.23**	**1.77**	**0.33**	**0.94**	**0.52**	**2.11**

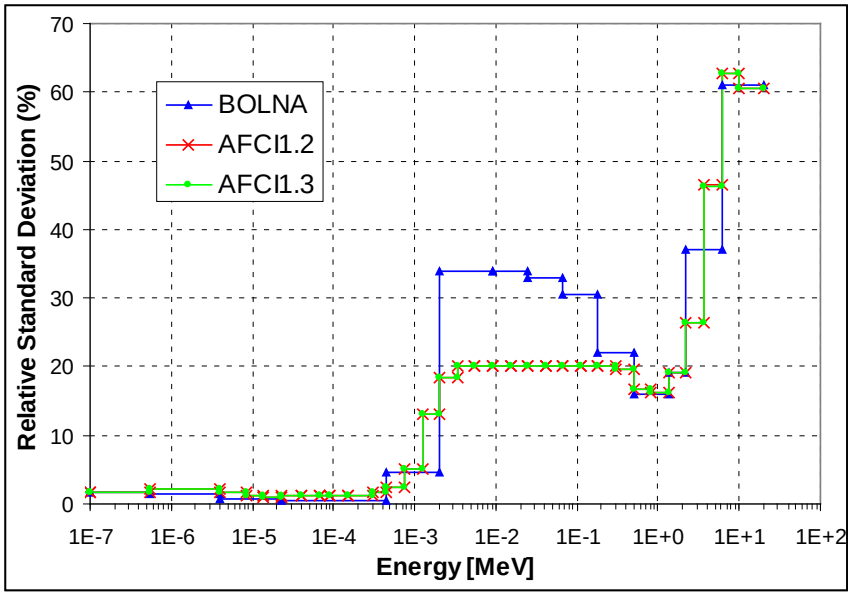


Uncertainty Breakdown (%) for EOC Multiplication Factor

Isotope	Fission	Capture	Elastic	Inelastic	Nu	Total
U238	0.05	0.37	0.30	1.20	0.17	**1.30**
Np237	0.01					**0.01**
Pu238	0.03				0.02	**0.03**
Pu239	0.26	0.19	0.03	0.17	0.14	**0.39**
Pu240	0.11	0.09		0.02	0.12	**0.19**
Pu241	0.19	0.01			0.01	**0.19**
Pu242	0.01					**0.01**
Am241						**0.01**
Am242m	0.01					**0.01**
Fe		0.04	0.02	0.27		**0.28**
Cr		0.01	0.02	0.01		**0.02**
Na23			0.08	0.14		**0.16**
Zr		0.02	0.01	0.12		**0.13**
Total	**0.34**	**0.42**	**0.31**	**1.26**	**0.26**	**1.43**



U235 Capture Brings Significant Uncertainty on k_{eff} of U-fueled Assemblies: e.g., ZPR6 Assy 6A (16% enriched) and GODIVA (94% enriched)



U235 Capture Relative Standard Deviations

Main Uncertainty Components (%) for the Multiplication Factor of ZPR6 Assembly 6A. Use of BOLNA Matrix

U235 Capture	2.18
U235 ν	0.55
U238 Capture	0.59
Total of all cross-sections	**2.39**

U235 Capture shows important effects related to the correlation terms of the matrix.

GODIVA Multiplication Factor Uncertainties (%)

	BOLNA diagonal	AFCI1.3 diagonal	BOLNA full	AFCI1.3 full
Isotope	**U235**	**U235**	**U235**	**U235**
ν	0.27	0.06	0.55	0.08
σ_{fiss}	0.14	0.11	0.26	0.26
σ_{inel}	0.34	0.26	0.46	0.47
σ_{el}	0.16	0.12	0.09	0.18i
σ_{capt}	0.44	0.26	0.90	0.71
Total	**0.65**	**0.41**	**1.18**	**0.88**
Overall [(a)]	**0.66**	**0.41**	**1.19**	**0.89**

[(a)] Total of all isotopes

Conclusions

- **Range of fuel cycles considered under U.S. advanced fuel cycle program is likely to expand in FY 2011**
  - Fuel cycle categories: once-through, modified open, and full recycle
- **Characteristics of systems different from those that have been considered in past studies**
  - Some existing assumptions need to be re-visited
- **Provides basis for re-evaluation of nuclear data needs**
  - Large uncertainties arising from U-235 nuclear data indicates need to further evaluation, and maybe re-visitation of covariance data and integral experiments