A Parameterization of the Neutronic Characteristics of Recyclable Uranium

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The Issue

- Large inventories of depleted uranium (DU) and reprocessed uranium (RU) will accumulate under most scenarios that envision partial fuel cycle closure
  - *There will be about 7 times more DU than RU, but the thermal-fissile content of the two reservoirs is about the same*
  - *By mass, these stockpiles dwarf those that circulate in many "closed" fuel cycles*

- Although it is not feasible to extract all of the energy from the fissionable atoms in these materials using LWRs, *their recycle can delay or even obviate (in the case of one RU strategy) their disposal*

- A single recycle of RU in LWRs can expand the effective uranium resource base by about 15%

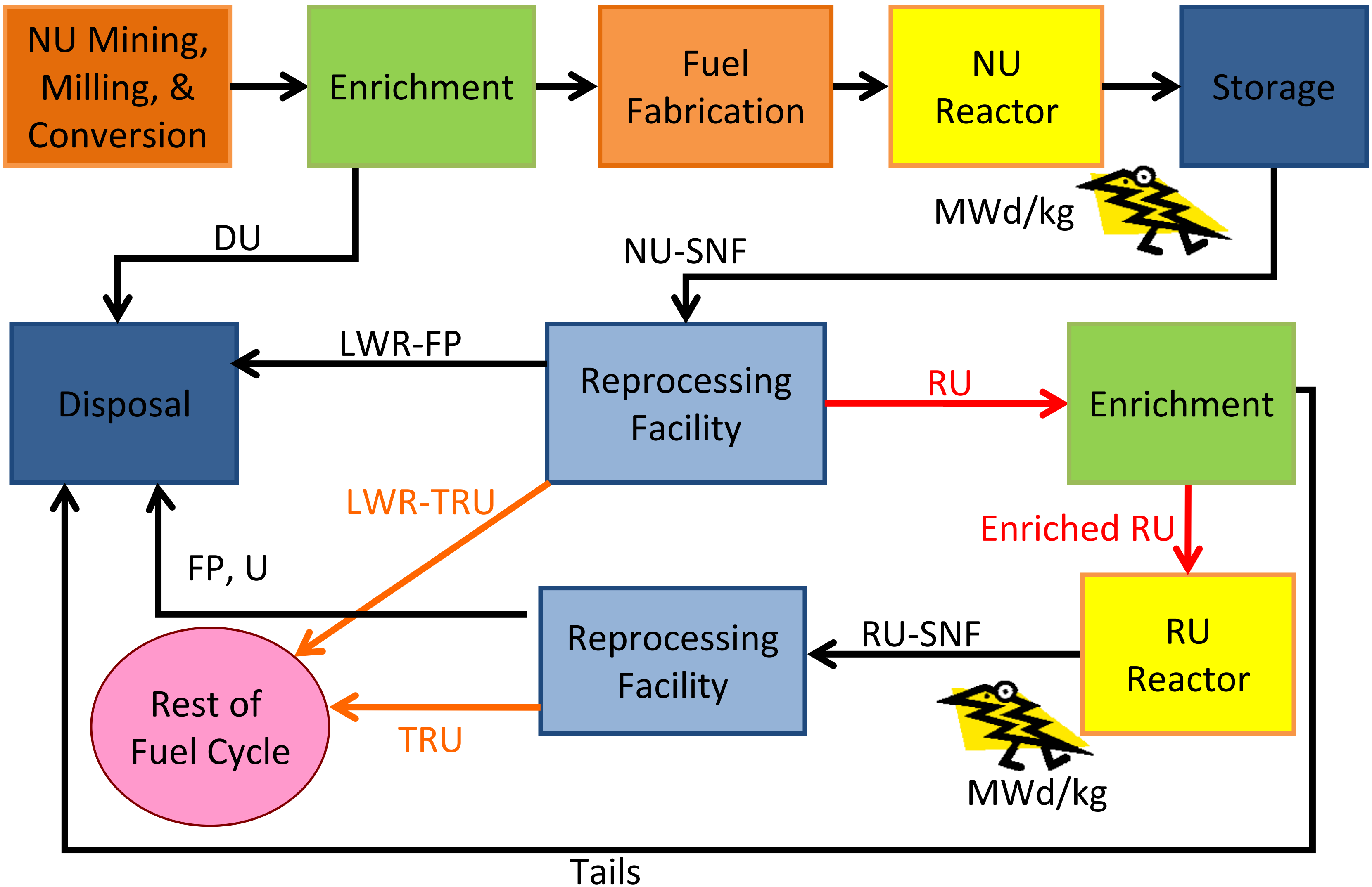
Outline

- This talk explores RU recycle in LWRs via enrichment and develops a simple cost analysis based on:
  - Reactor physics (RU in-core performance parameterized according to U^{235} & U^{236} content, fuel management, discharge burnup)
  - Enrichment (multi-isotope enrichment cascade model with separation factors determined by cascade mass flow minimization)
  - Unit Costs (modules A, B, C1, D, K1, K2 from Advanced Fuel Cycle Cost Basis Report, Public Release of April 2007)

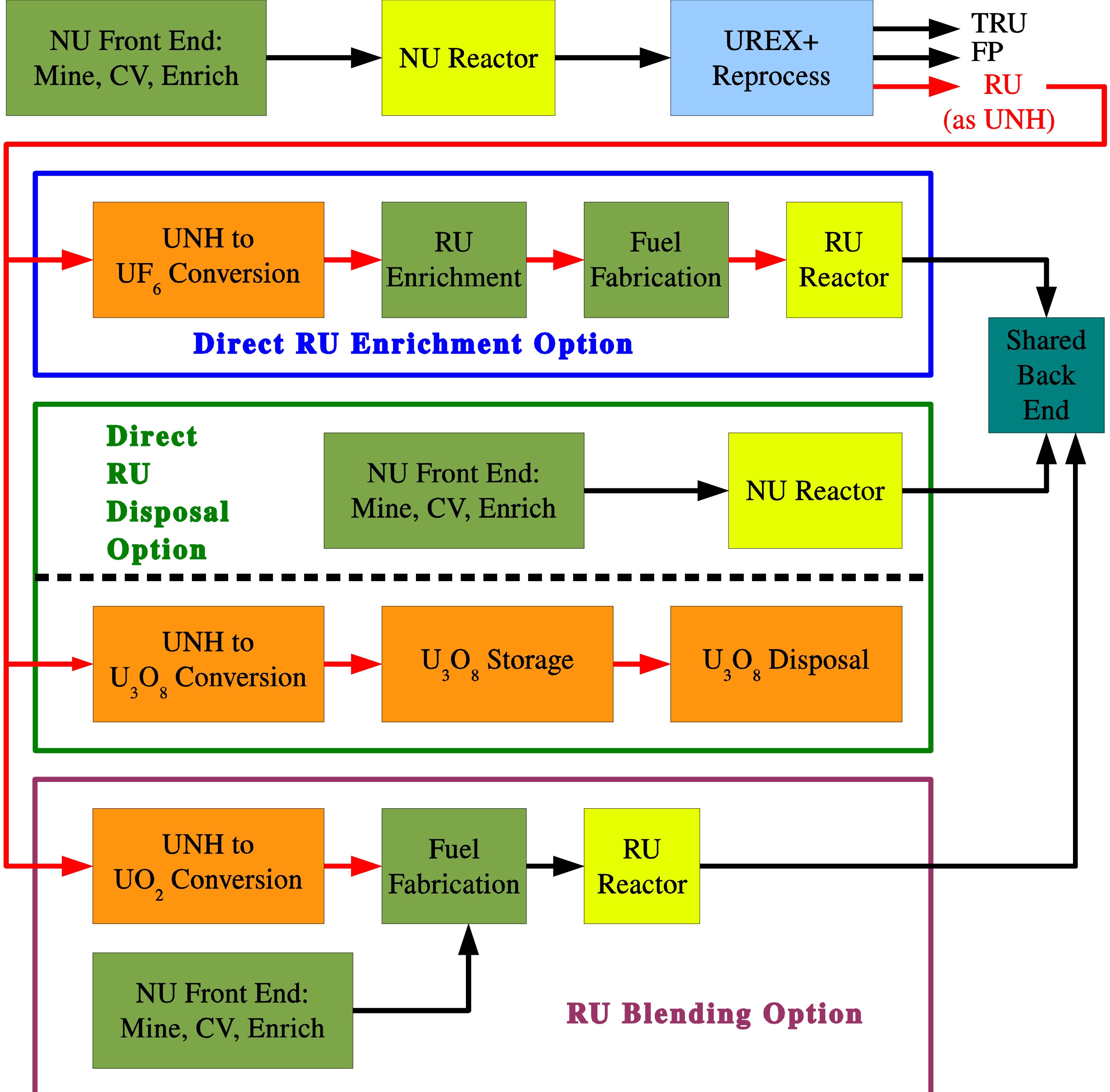
RU: Nominal Strategy in the US

- Uranyl Nitrate Hexahydrate concentration and conversion to a stable form (U_3O_8)
  - Cost range: \$6 / \$7 / \$12 / kgRU (Module K2) if polishing (aqueous ^{232}U daughter removal) is not necessary
  - \$20 / \$30 / \$41 / kgRU if polishing (aqueous ^{232}U daughter removal) is necessary
- Two subsequent options/stages in disposal process:
  - Long term (~40 yr) storage: \$6 / 12 / 30 /kgRU
  - Repository disposal: \$61 / 72 / 93 /kgRU
- Costs from 2007 AFCI report: LOW / MID / HIGH

Enrichment Strategy



Three RU Disposition Options



Comparing These Strategies

- The three options shown on the previous slide represent either
  - recycle of the RU, or
  - disposal of the RU plus use of NU to generate the energy that was foregone when the RU was not used.
- We must know how much energy can be obtained from the RU given
  - a discharge burnup target that assumes parity between RU- and NU-bearing fuels,
  - the isotopics of the enriched RU obtained via a multicomponent enrichment cascade model.

Iterative Approach

- We present an iterative approach that uses effective one-group cross sections prepared via transport calculations to
  - compute the attainable discharge burnup given the isotopic composition of an input stream,
  - update the enrichment cascade design to alter the ^{235}U enrichment of its output stream based on the results of the discharge burnup estimate,
  - calculate the composition of the discharged fuel (a Bateman equation solver, but parameterized by the fresh fuel composition).

Conceptual Walkthrough of Burnup and Criticality Calculation

- The burnup-dependent composition and reactivity of nuclear fuel and non-actinide reactor components are calculated via superposition of isotope-by-isotope burnup calculations performed using ORIGEN2.2.

- The ORIGEN2.2 one group cross section libraries are themselves prepared from neutron transport calculations performed on a representative unit of the core using MCNPX.

Conceptual Walkthrough, 2).

- For a given reactor type, the burnup model constructs, as a function of fluence F [n/kilobarn], the following pointwise data libraries per unit mass of the i^{th} isotope present in the fresh fuel:
  - isotopic transformation matrices m_{ij} [kg of daughter isotope j/kg of parent isotope i],
  - neutron production rate vectors p_i [n/s/kg per flux],
  - neutron destruction rate vectors d_i [n/s/kg per flux], and
  - burnup vectors B_i [MWd/kg].

- This burnup calculation is run for a unit mass of each actinide, providing a depiction of the evolution of the unit mass with fluence.   These libraries only need to be generated once for a given rector type.

Conceptual Walkthrough, 3).

- The specific burnup, neutron production rate and neutron destruction rate vectors describe the contribution of the i^{th} isotope to the neutron balance and cumulative energy production.

- The isotopic composition matrix lists the mass of hundreds of daughter isotopes per unit mass of the parent isotope.

- The composition of the fuel at a specified fluence is determined by summing the initial-mass-weighted compositions of each parent isotope at that fluence. For example, if the initial mass fraction of the i^{th} isotope (of I total isotopes in the initial fuel) is w_i, the fuel composition vector $m_j(F)$ at fluence F may be found from

$$m_j(F) = \sum_{i=1}^{I} m_{ij}(F) w_i(F).$$

Conceptual Walkthrough, 4).

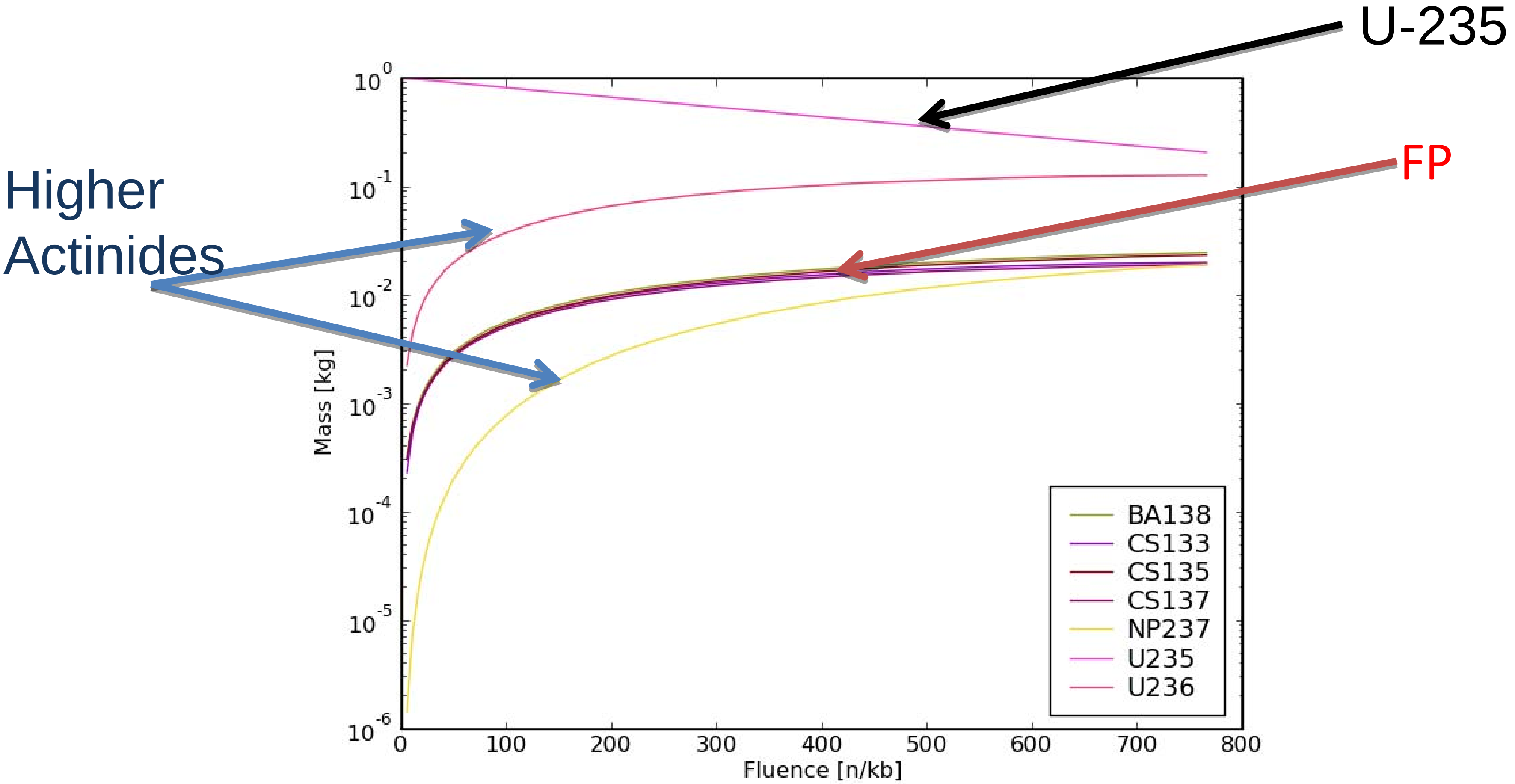
- To obtain BUd, the discharge burnup for a given initial fuel composition, the burnup B and multiplication factor k are found as functions of fluence F.
- $k_\infty(F)$ is calculated from the ratio of the initial-mass-weighted neutron production to destruction:

$$k_\infty(F) = \frac{\sum_{i=1}^{I} m_i(F) w_i(F) p_i(F)}{\sum_{i=1}^{I} m_i(F) w_i(F) d_i(F)}.$$

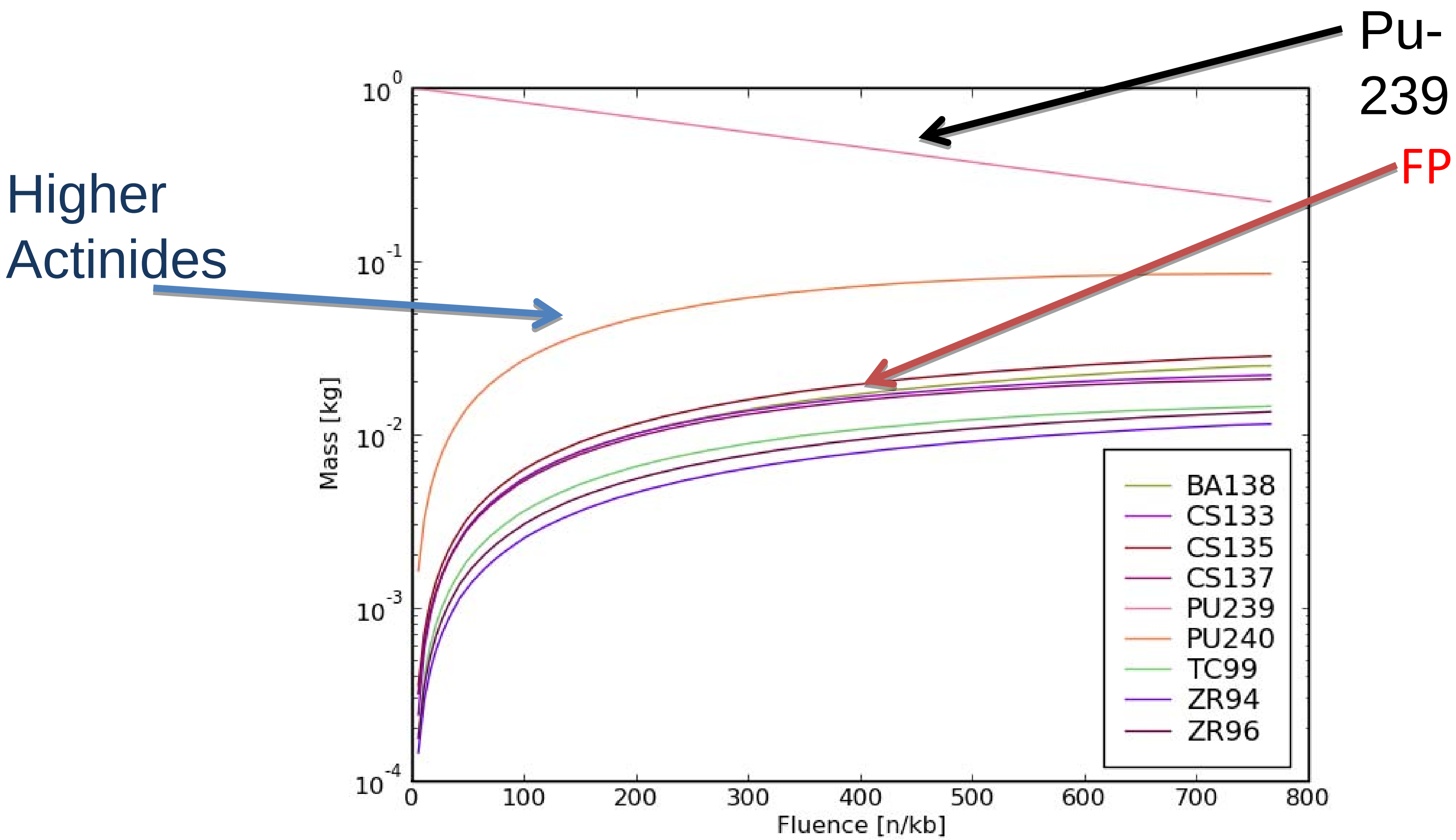
- A non-leakage probability P_{NL} is applied, so that $k(F) = k_\infty(F)P_{NL}$.
- Given k(F), the fluence at which the reactor becomes sub-critical is obtained. And used to compute BUd from B(F).
- The process can be inverted if a BUd target is known and the initial composition is required.

Burnup Model: Isotopics – ^{235}U

The following figures illustrate a small portion of the $m_{ij}(F)$ isotopic transformation matrices. Once the discharge fluence is known, the composition of discharged fuel is obtained from these precomputed data.

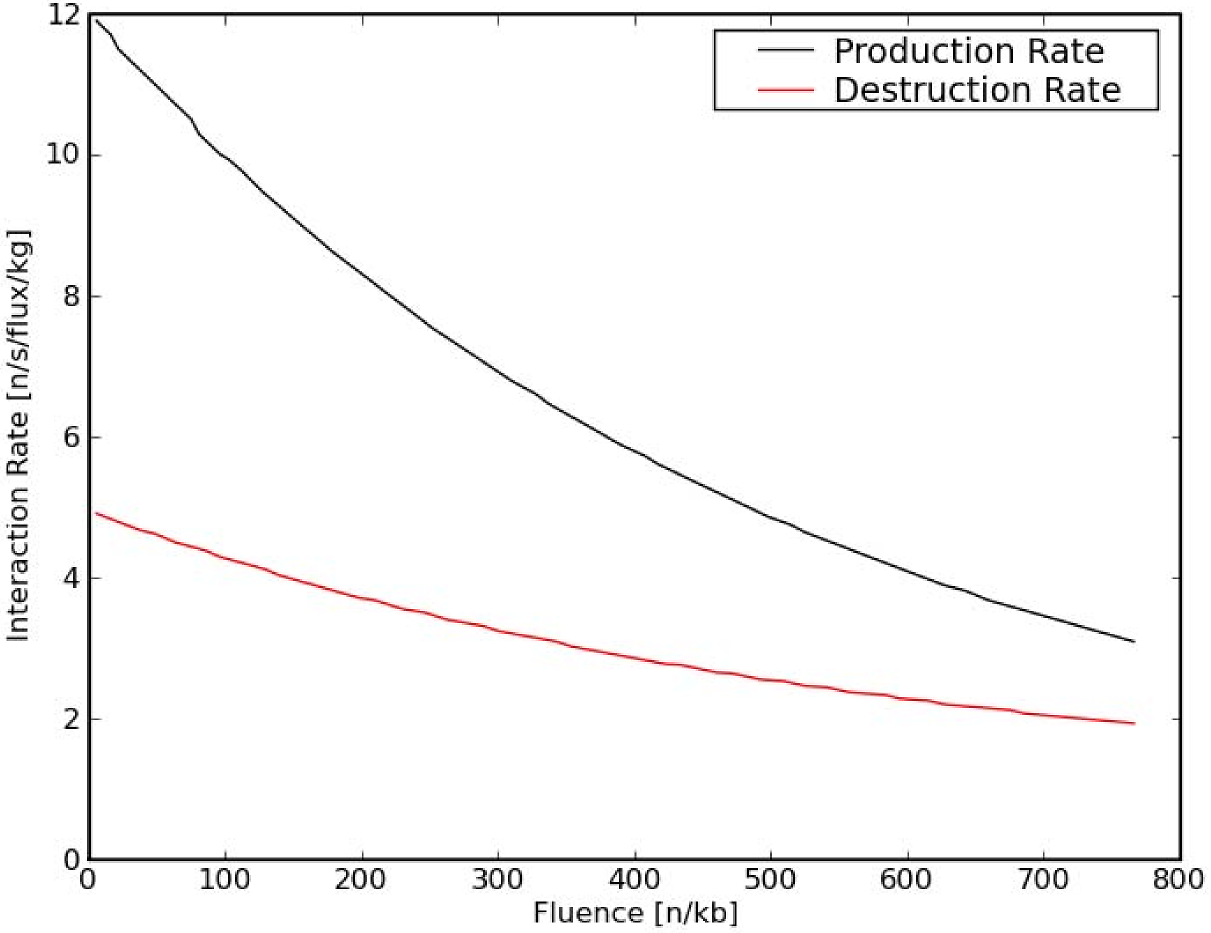


Burnup Model: Isotopics – Pu239



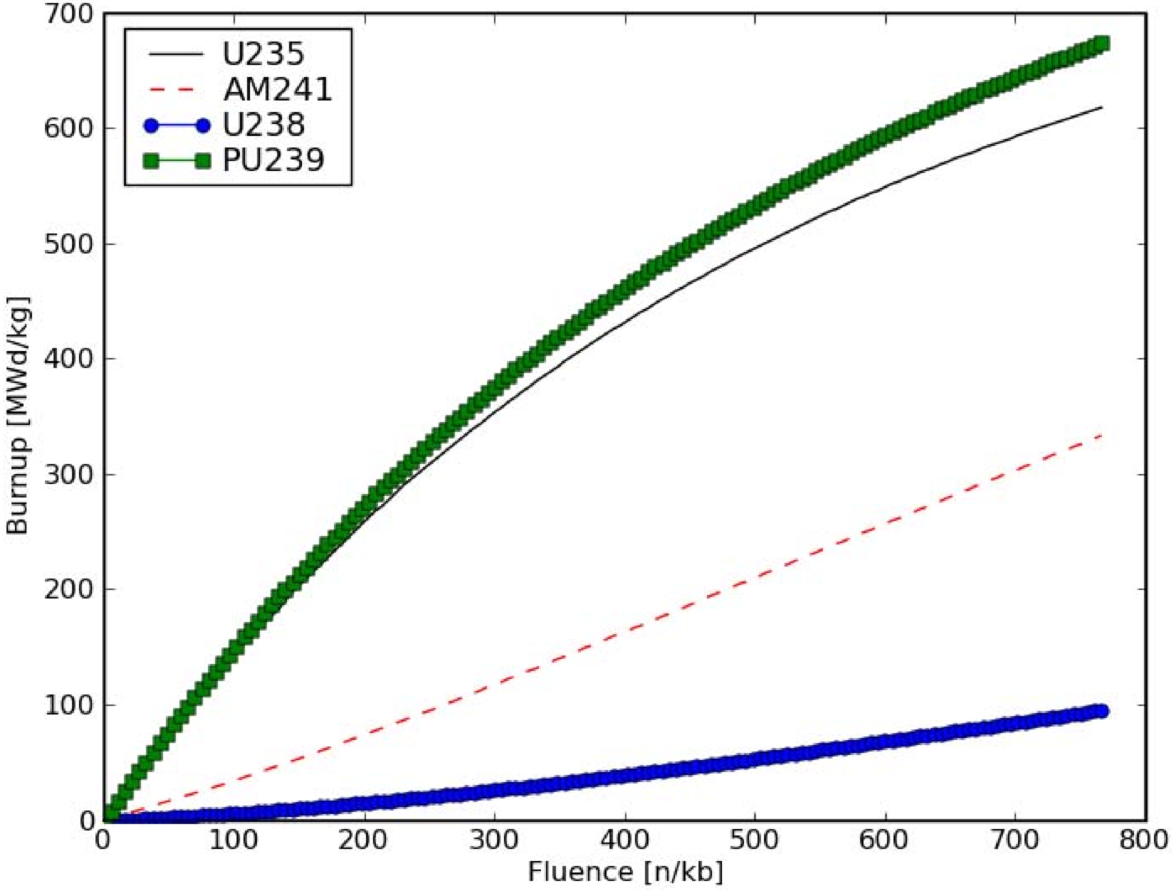
Burnup Model – Production and Destruction Rates

Neutron Production and Destruction Rates versus Fluence for an Initial Unit Mass of ^{239}Pu, Na cooled 0.5 CR Fast Reactor (ABR)



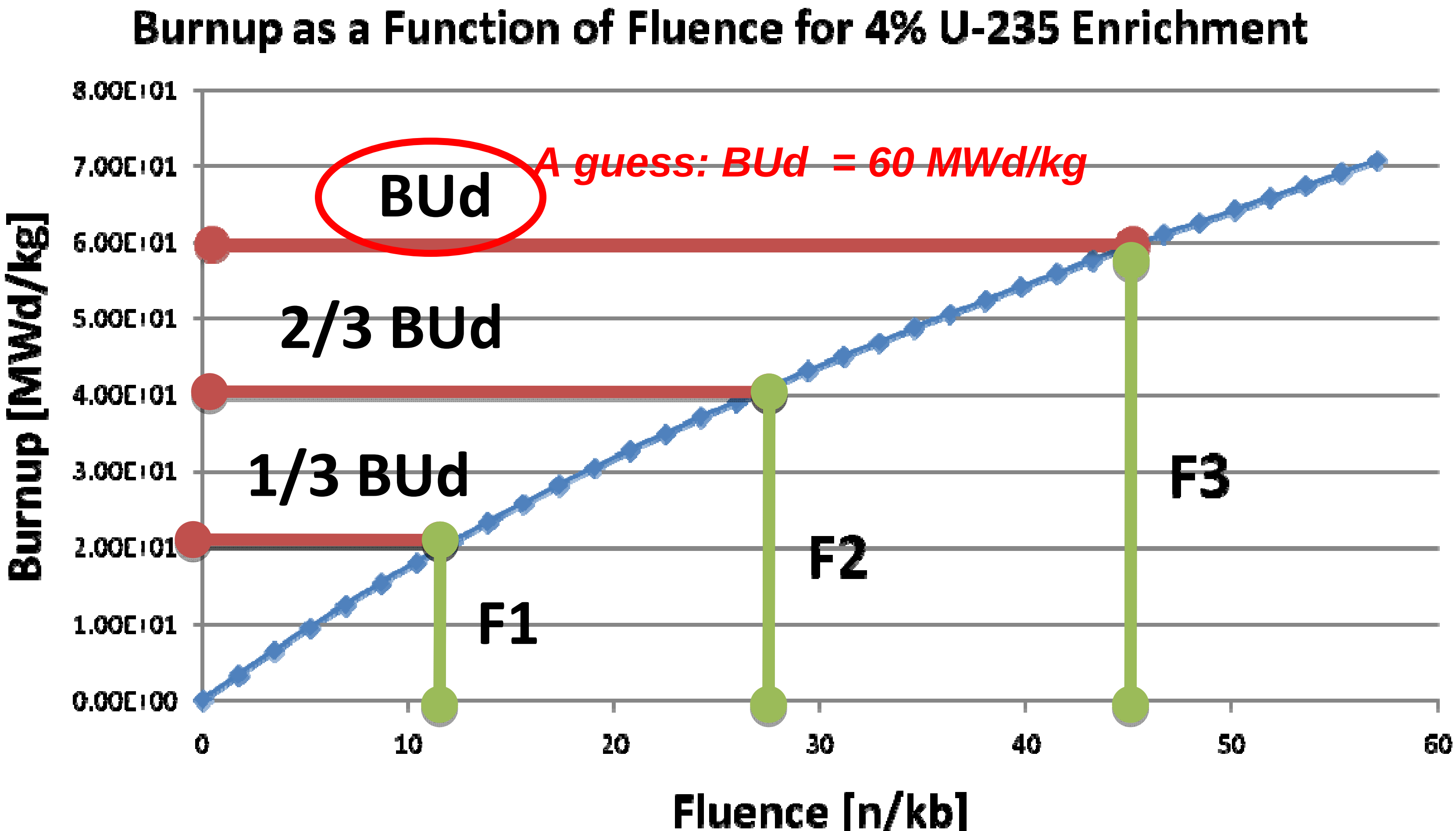
Burnup Model – Specific Burnup

Burnup versus Fluence for an Initial Unit Mass of Selected Nuclides in an Na cooled 0.5 CR Fast Reactor (ABR)



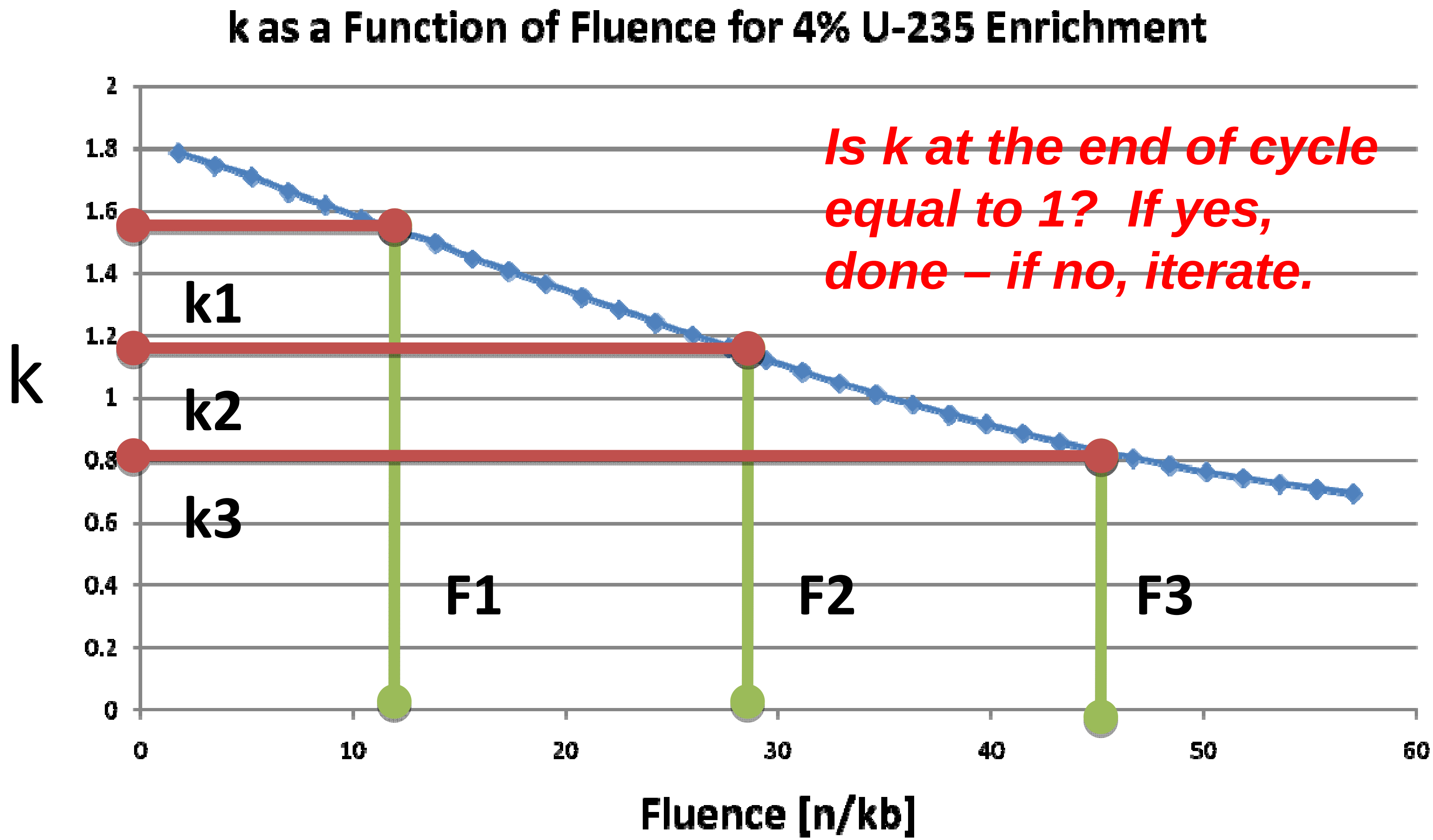
Construct BU-Fluence Relationship

Illustrative case: using the approach to calculate the discharge burnup of 4% enriched UOX loaded to a generic PWR with 3-batch fuel management:



Determine fluence level of each batch at end of cycle…

Construct K_{eff} – Fluence Relationship



Material Balance: Enrichment Calculations

To obtain fuel that is burnable to 51 MWd/kg from reprocessed uranium obtained from 51 MWd/kg PWR SNF, the following cascade was used:

N, enrichment stage number:	27.43
M, stripping stage number:	15.06
M* Cascade key weight	236.5
L/F, total flow rate over feed flow rate (minimized):	328.4
SWU per 1 kg Feed:	0.851
SWU per 1 kg Product:	7.863

Isotopic Composition (weight percent):

	U-234	U-235	U-236	U-238
Product	***0.147***	***5.503***	***2.84***	***91.50***
Feed	0.0183	0.818	0.610	98.55
Tails	2.747×10^{-5}	0.250	0.339	99.40

Mapping the ^{235}U and ^{236}U Content in SNF

- In the US, the EIA maintains a database of initial enrichments and discharge burnups for legacy spent fuel assemblies.
- We use our model to generate the isotopic (specifically ^{235}U and ^{236}U) composition of this SNF based on these data.

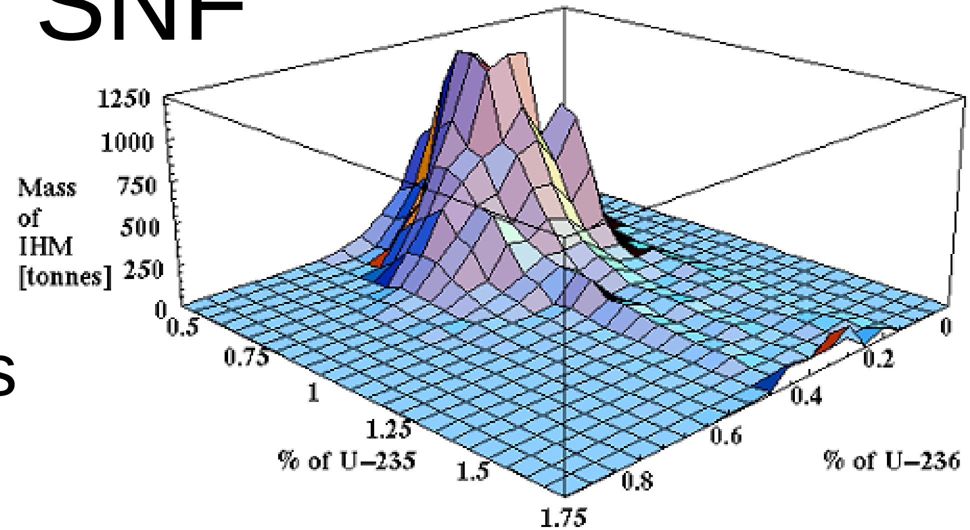
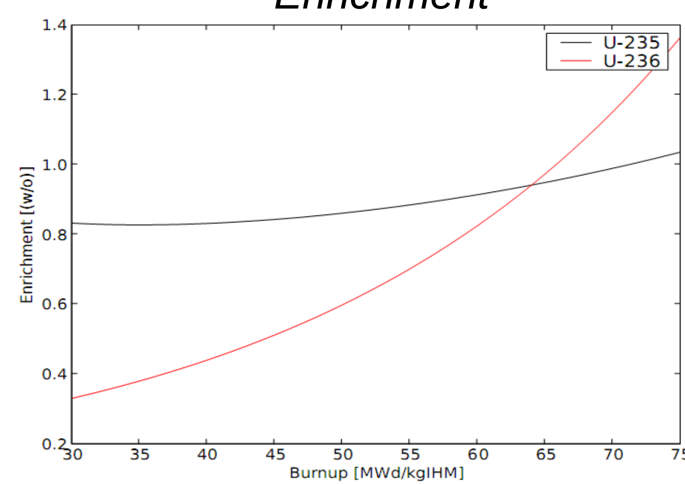
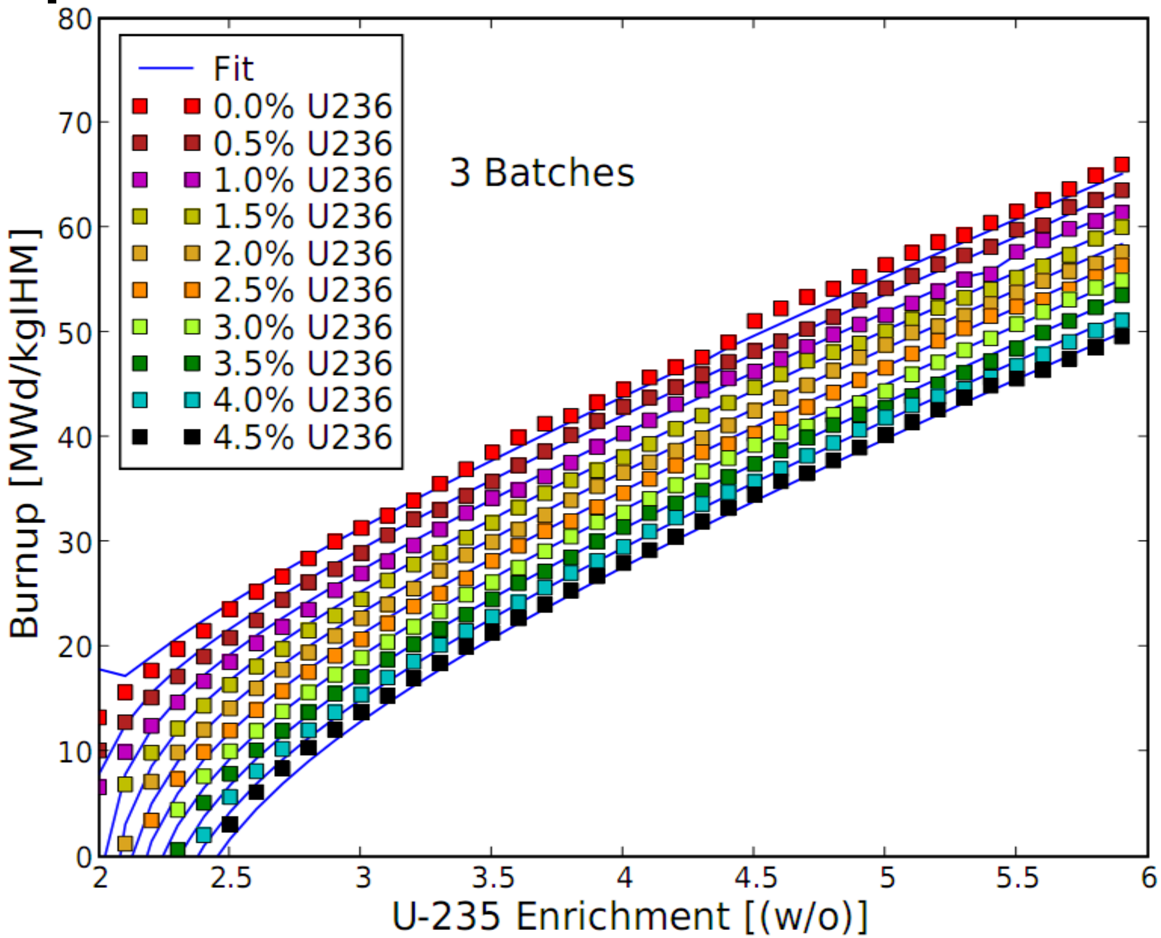


Figure. Discharge Isotopics When Model is Used to Predict Initial U-235 Enrichment



Parameterized Result: Discharge Burnup Given ^{235}U and ^{236}U Content



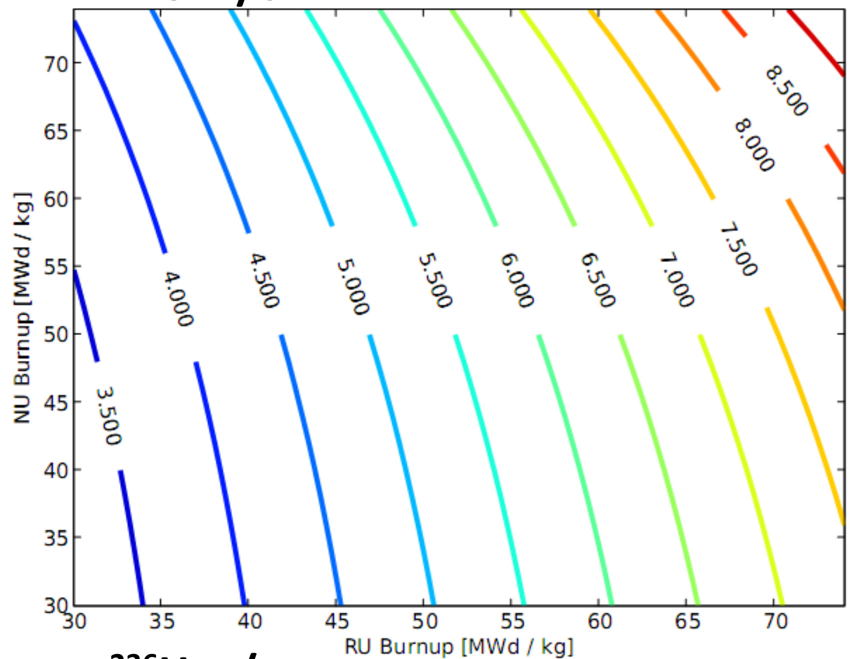
Given the uranium compositions depicted on the previous slide as well as the degree of freedom afforded by the enrichment cascade separation factors, a wide range of (235U, 236U) isotopics arise in enriched RU.

Parameterization: LEU Burnup Specified

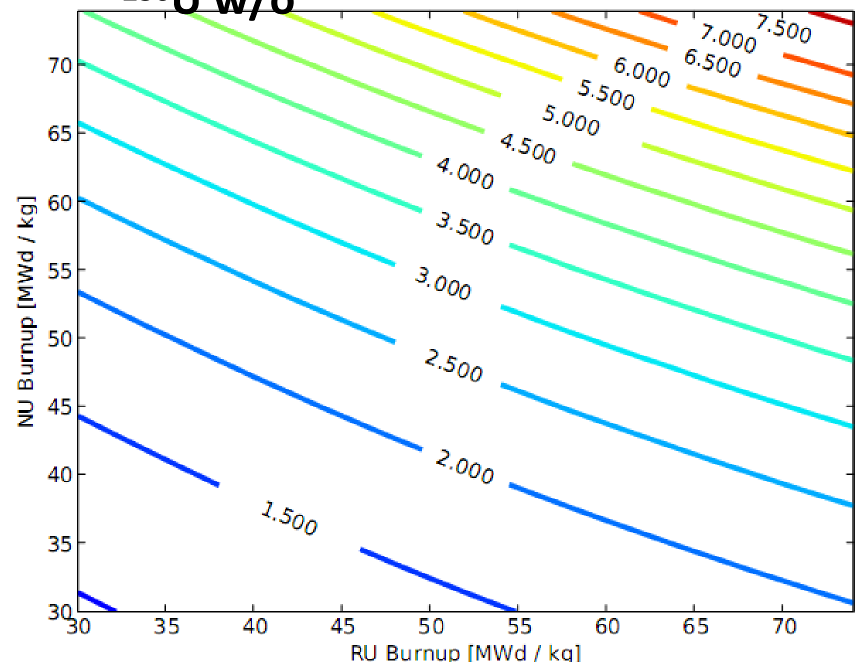
To perform a cost benefit analysis of RU recycle, we seek to answer the question, “given typical used LEU fuel of known burnup, is it worthwhile to enrich and recycle its RU?”

The parameterization shown here provides the information needed to answer that question.

^{235}U w/o



^{236}U w/o



Fuel Cycle Cost Comparison

Given the calculated fuel cycle material balances, unit costs from the Advanced Fuel Cycle Cost Basis Report, and a consistent methodology, fuel cycle costs in mills/kWh(e) can be calculated and compared for the three options.

- The cost calculation is a simple one, a summation of (Unit cost * mass flow) / kWh(e).
    - **Back end cost components that are common to both scenarios, e.g., reprocessing, were not included.**

- A thermal to electric conversion efficiency of 33% was assumed.
- Since most of the costs and revenues would be incurred within two years of one another, no discounting is employed for the most part.
    - The exception is RU_3O_8 repository disposal, which follows 40 years of storage. This cost component was discounted at 5% p.a.

Unit Costs

	LO	**Most Likely**	HI	UNIT	AFC CBR Module
U Mining, Milling	25	**108***	240	$/kgU	A
U_3O_8 to UF_6 Conversion	5	**10**	15	$/kgU	B
Enrichment	80	**105**	130	$/SWU	C1
(NU)OX Fabrication	220	**220**	264	$/kgHM	D
(RU)OX Fabrication	290	**290**	350	$/kgHM	D1-1
DU Disposal	5	**10**	50	$/kgU	K1
Reprocessed UNH to UF_6 Conversion	6	**7**	12	$/kgU	K2
Reprocessed UNH to U_3O_8 Conversion	4	**5**	10	$/kgU	K2
Reprocessed UNH to UO_2 Conversion		**41**		$/kgU	K2
RU_3O_8 Storage (40 yr)	6	**12**	30	$/kgU	K2
RU_3O_8 Disposal	61	**72**	93	$/kgU	K2

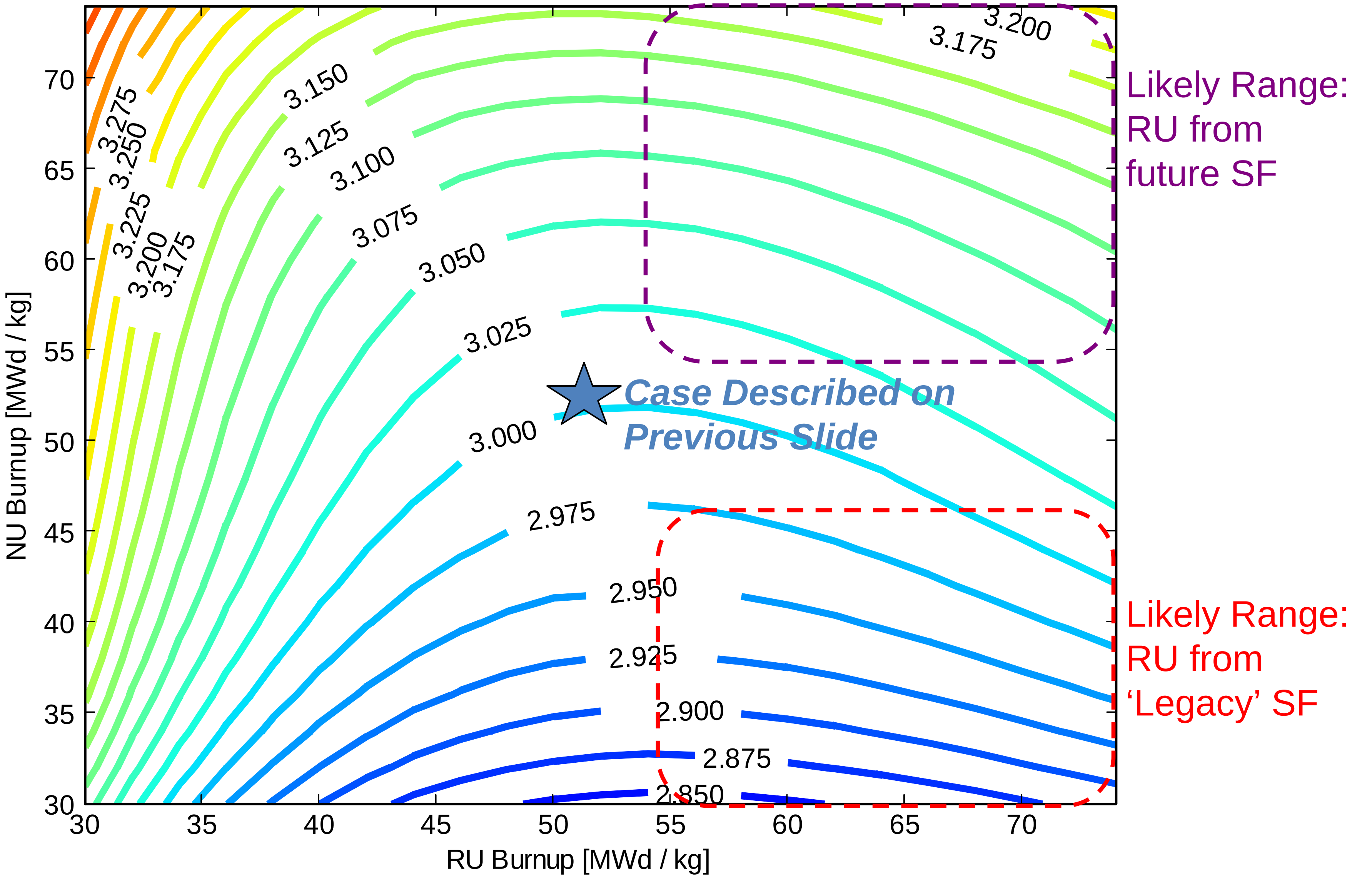
* Mean

Fuel Cycle Costs

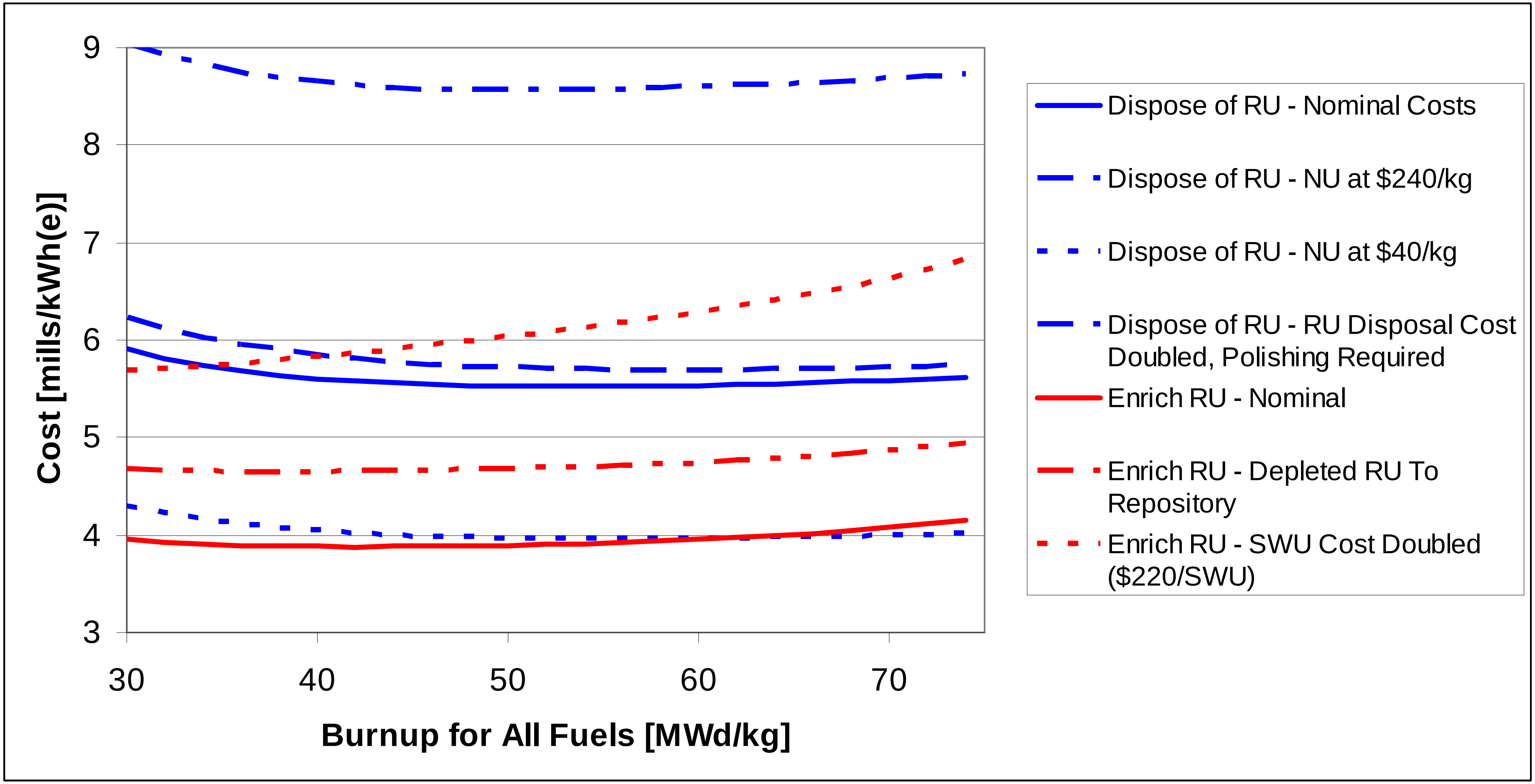
The costs arrived at for the three options are given in the table.

Units: mills/kWh(e)	*DISPOSE*	*ENRICH*	*BLEND*
U Mining, Milling	*2.45*	*0*	*2.28*
U_3O_8 to UF_6 Conversion	*0.23*	*0*	*0.21*
Enrichment	*1.79*	*2.14*	*1.77*
UOX Fabrication	*0.72*	*0.73*	*0.70*
DU Disposal	*0.20*	*0.18*	*0.20*
Rep UNH to UF_6 Conversion	*0*	*0.85*	*0*
Rep UNH to U_3O_8 Conversion	*0.011*	*0*	*0*
Rep UNH to UO_2 Conversion	*0*	*0*	*0.05*
RU_3O_8 Storage (40 yr)	*0.028*	*0*	*0*
RU_3O_8 Disposal	*0.024*	*0*	*0*
Total	*5.48*	*3.89*	*5.20*

Front End Cost Map for RU Enrichment



Sensitivities



A less optimistic set of assumptions for the RU cycle (e.g., polishing required at multiple steps, tails from RU enrichment must be disposed of in the same way as RU itself) changes the picture considerably.

Commentary

- As the unit costs are currently established in the AFC Cost Basis Report, it appears that RU enrichment is cost effective. Why?
  - since we obtain a separated U stream from UREX+ at no extra cost, it's worthwhile to extract its value rather than buying NU at $108/kg
  - Cost premium associated with dedicated RU enrichment cascade is uncertain and would likely depend on scale of RU enrichment enterprise

- The blending option does not conserve the resource or reduce SWU/kWh(e), nor is it cheaper than not using the RU at all but rather disposing it.
  - it's the only sustainable pathway short of breeding to reducing actinide 'waste' under a 'closed' fuel cycle scenario from about 0.9 kg per kg of used fuel to zero, so it may bear consideration.
  - RU disposal costs appear small when compared to fuel cycle costsso the economics of this option are not favorable.