CHARACTERIZING THE UNITED STATES NUCLEAR USED FUEL INVENTORY USING THE CYCLUS FUEL CYCLE SIMULATOR

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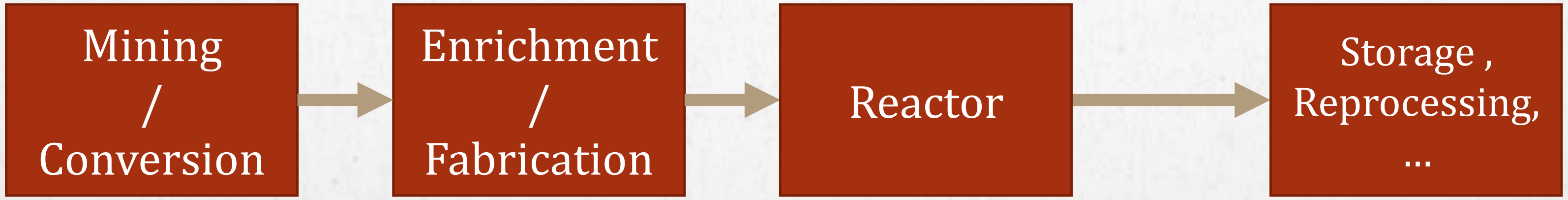
OVERVIEW

1. Introduction to Cyclus and **Bright-lite**
2. Introduction to the **methodology** of Bright-lite
3. **Description** of the US fleet study
4. **Results**
5. **Conclusions** and future work

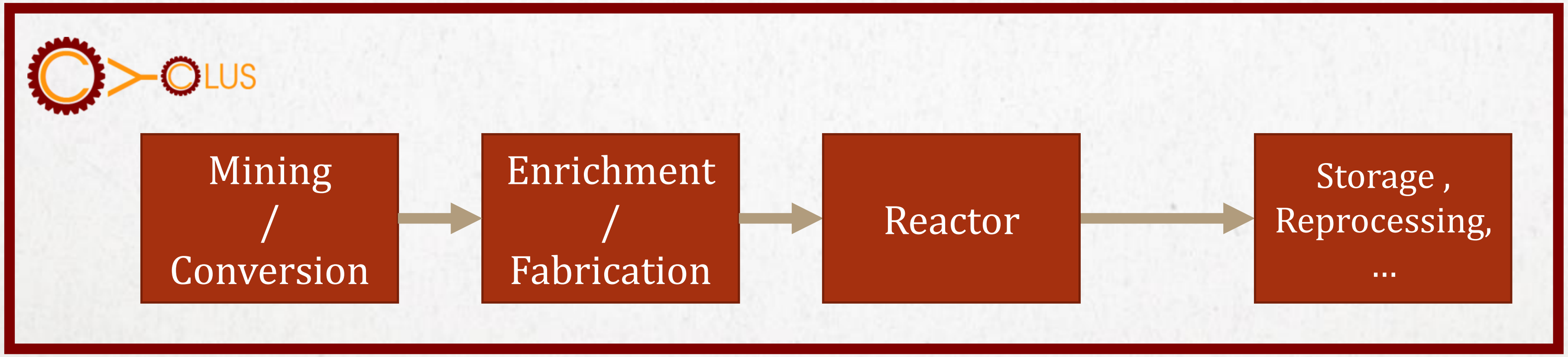
NUCLEAR FUEL CYCLE SIMULATORS

- Nuclear fuel cycle (NFC) simulators enable the study of fuel cycle and reactor technology options by informing users on
  - future supply and demand of **materials**
  - **energy** production
  - **waste** inventories
- Higher **accuracy** calculations require more **costly** computations



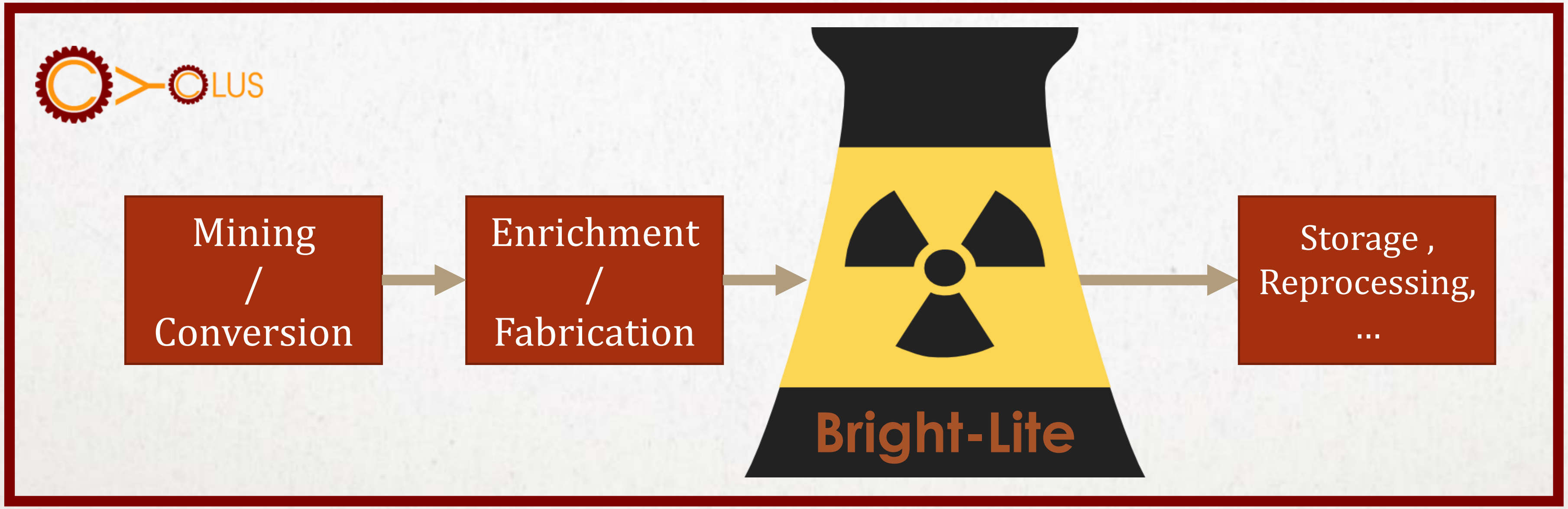
CYCLUS

- Agent-based nuclear **fuel cycle simulator**
- Enable a broad spectrum of fuel cycle simulation while providing easy entry for new users and **agent developers**



BRIGHT-LITE

- A medium fidelity reactor modeling software used in conjunction with Cyclus.
- Can measure various reactor characteristics including; burnup, isotopic vectors, criticality, and conversion ratio (CR).

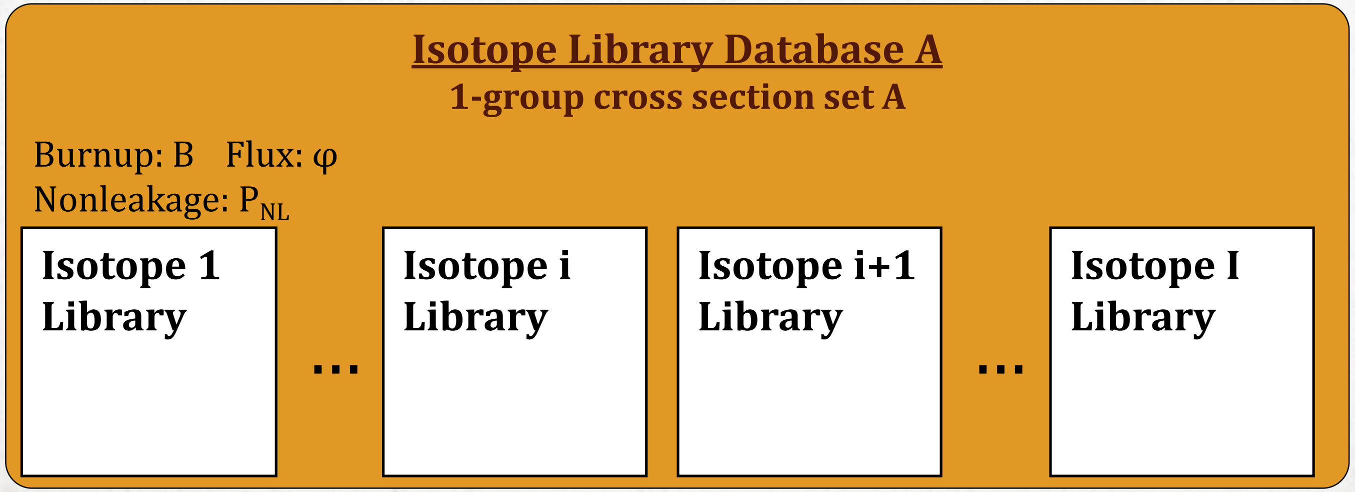


BRIGHT-LITE

- **Characteristics** of the code are:
  - **Quick** execution
  - **Flexibility** for various reactor technologies
  - Calculating necessary parameters such as discharge **burnup**
  - Tracking material **compositions**
  - Has two modes of operation
    - Forward
    - Blending

FLUENCE-BASED NEUTRON BALANCE APPROACH

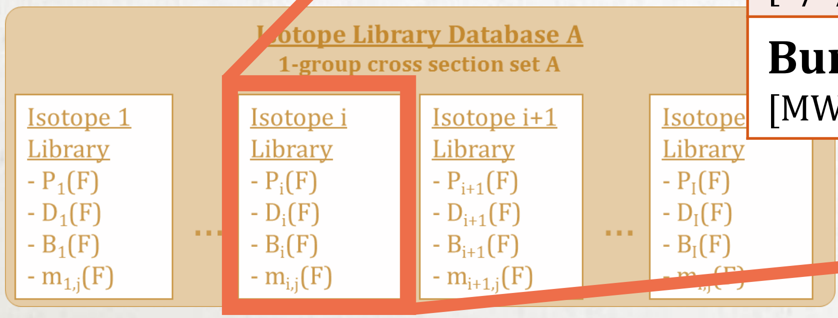
- One energy group cross section libraries used to **pre-calculate and parameterize burnup and transmutation** calculations
- The results of these calculations are saved in **isotope library <u>databases</u>** for use during runtime
- Each database describes a specific reactor under specific operating conditions



(**Fluence** is **flux** integrated over time)

FLUENCE-BASED NEUTRON BALANCE APPROACH

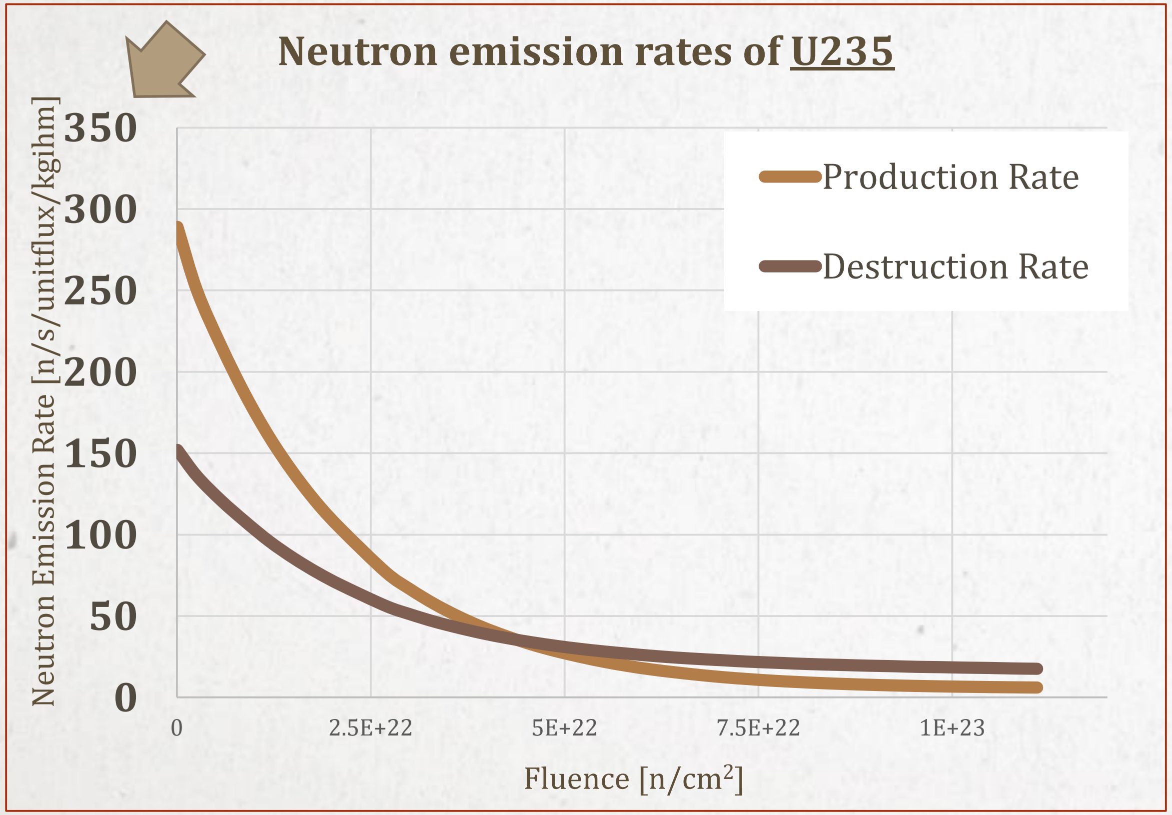
- Example **U-235** isotope library from a LWR reactor database
- Transmutation matrix not shown

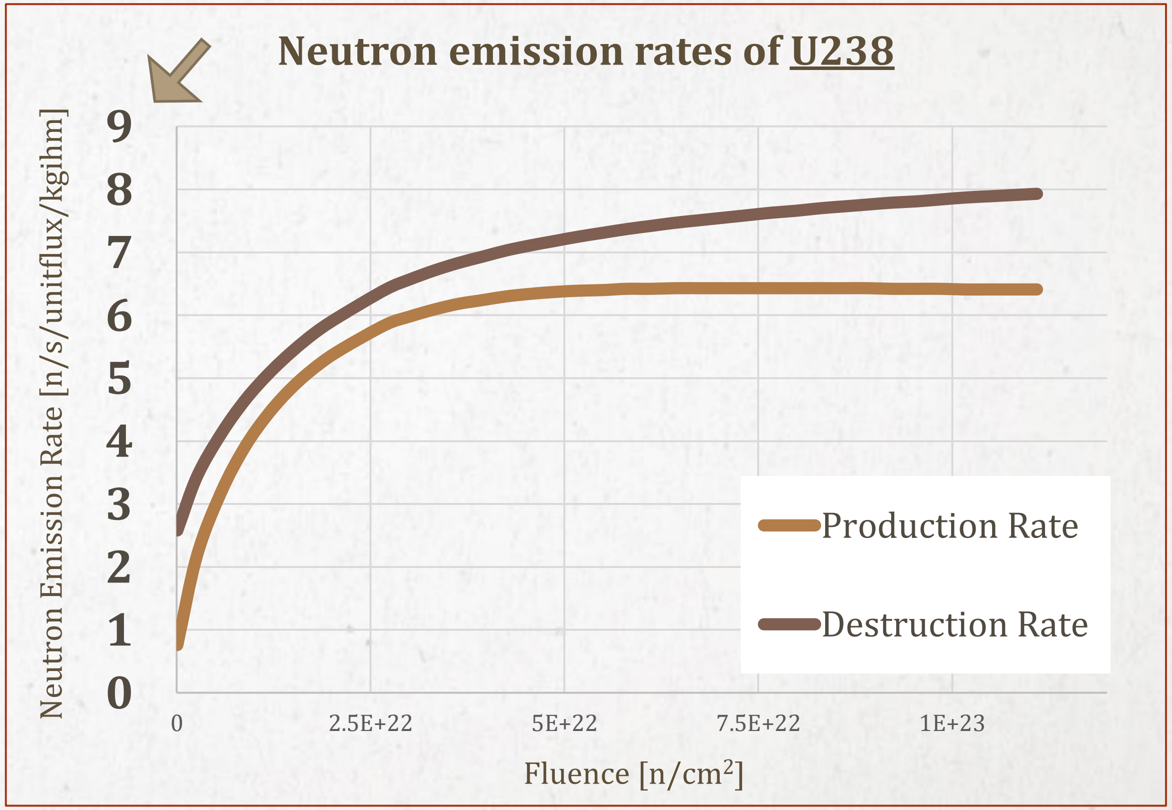


Vector	F_1	F_2	F_3	F_4	…
Fluence [n/cm^2]	0	2.59E+21	5.70E+21	8.81E+21	…
Neutron Prod(F) [n/s/ϕ/kg]	289	250	216	186	…
Neutron Dest(F) [n/s/ϕ/kg]	152	136	121	108	…
Burnup(F) [MWd/kg]	0	108.5	201.7	282.1	…

(**Fluence** is **flux** integrated over time)

FLUENCE-BASED NEUTRON BALANCE APPROACH





USING COMPOSITION TO GET FUEL LIBRARY

Isotope Library Database A

1-group cross section set A

U-235 Library
- $P_{U-235}(F)$
- $D_{U-235}(F)$
- $B_{U-235}(F)$
- $m_{U-235,j}(F)$

…

U-238 Library
- $P_{U-238}(F)$
- $D_{U-238}(F)$
- $B_{U-238}(F)$
- $m_{U-238,j}(F)$

Th-232 Library
- $P_{Th-232}(F)$
- $D_{Th-232}(F)$
- $B_{Th-232}(F)$
- $m_{Th-232,j}(F)$

…

Pu-239 Library
- $P_{Pu-239}(F)$
- $D_{Pu-239}(F)$
- $B_{Pu-239}(F)$
- $m_{Pu-239,j}(F)$

Input Comp

U-235: X_{U235}

U-238: X_{U238}

Th-232: X_{Th232}

Pu-239: X_{Pu239}

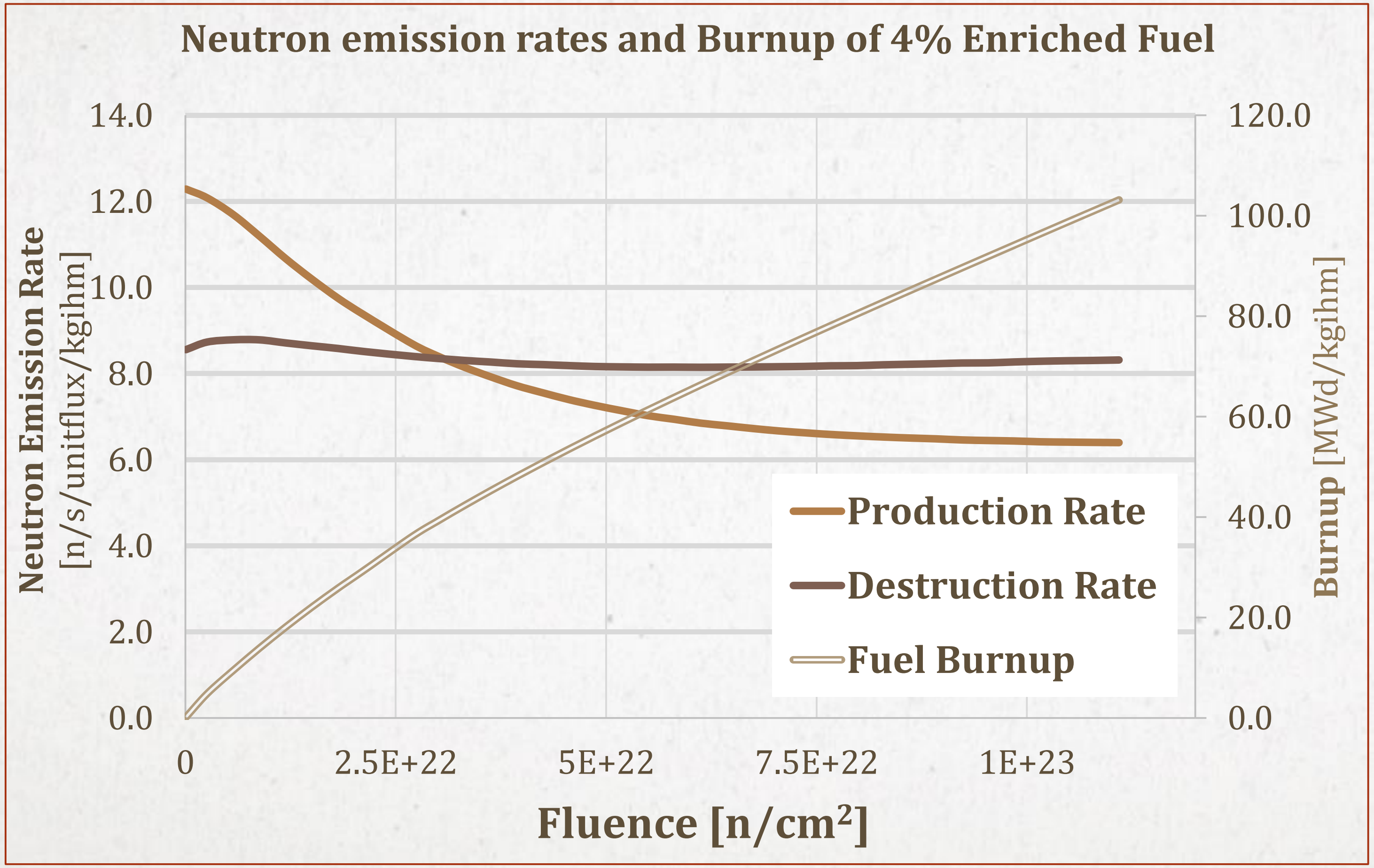
…

Fuel Library

- $P(F)$
- $D(F)$
- $B(F)$
- $m_j(F)$

Fuel composition is used to combine isotopes to generate a fuel library

FUEL LIBRARY



- PWR loaded with 96% U238 and 4% U235
- The neutron production rate eventually drops below the neutron destruction rate
- Burnup is found from calculating discharge fluence

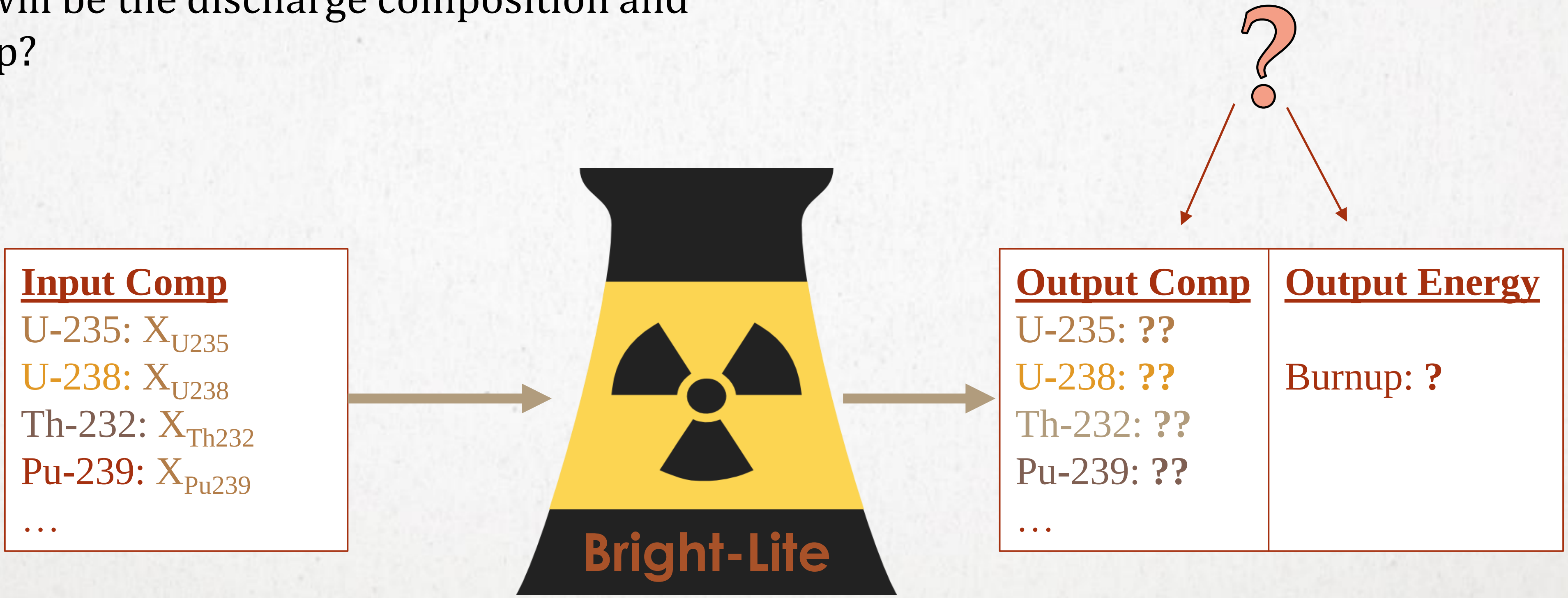
FINDING DISCHARGE FLUENCE

- Core criticality cannot be sustained when production rate is lower than destruction rate
  - Fuel is discharged when $k < 1$
- Fuel can be discharged on other conditions such as conversion ratio and maximum fluence
- Several other factors can be considered when calculating discharge fluence.
  - Effects of structural materials on the neutron balance
  - Effect of nonleakage probability
  - Separation of fuel into batches

FORWARD MODE

Forward mode:

Given an input fuel composition vector, what will be the discharge composition and burnup?



BLENDING MODE

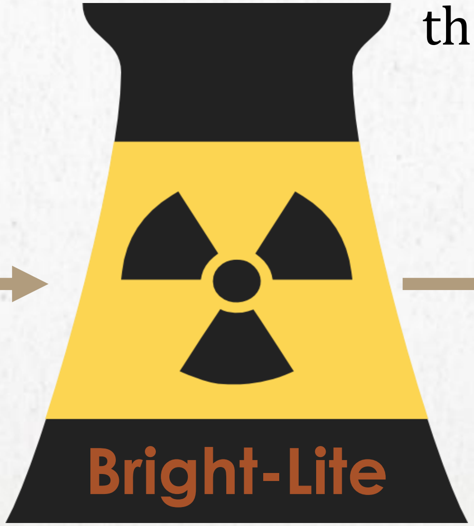
Blending mode:
Given a target burnup and two or more input mass streams (e.g., DU and TRU), how do we blend the streams and what's the output composition?

Stream 1
U-235: X_{U235}
U-238: X_{U238}
Th-232: X_{Th232}
Pu-239: X_{Pu239}

Stream 2
U-235: Y_{U235}
U-238: Y_{U238}
Th-232: Y_{Th232}
Pu-239: Y_{Pu239}

?

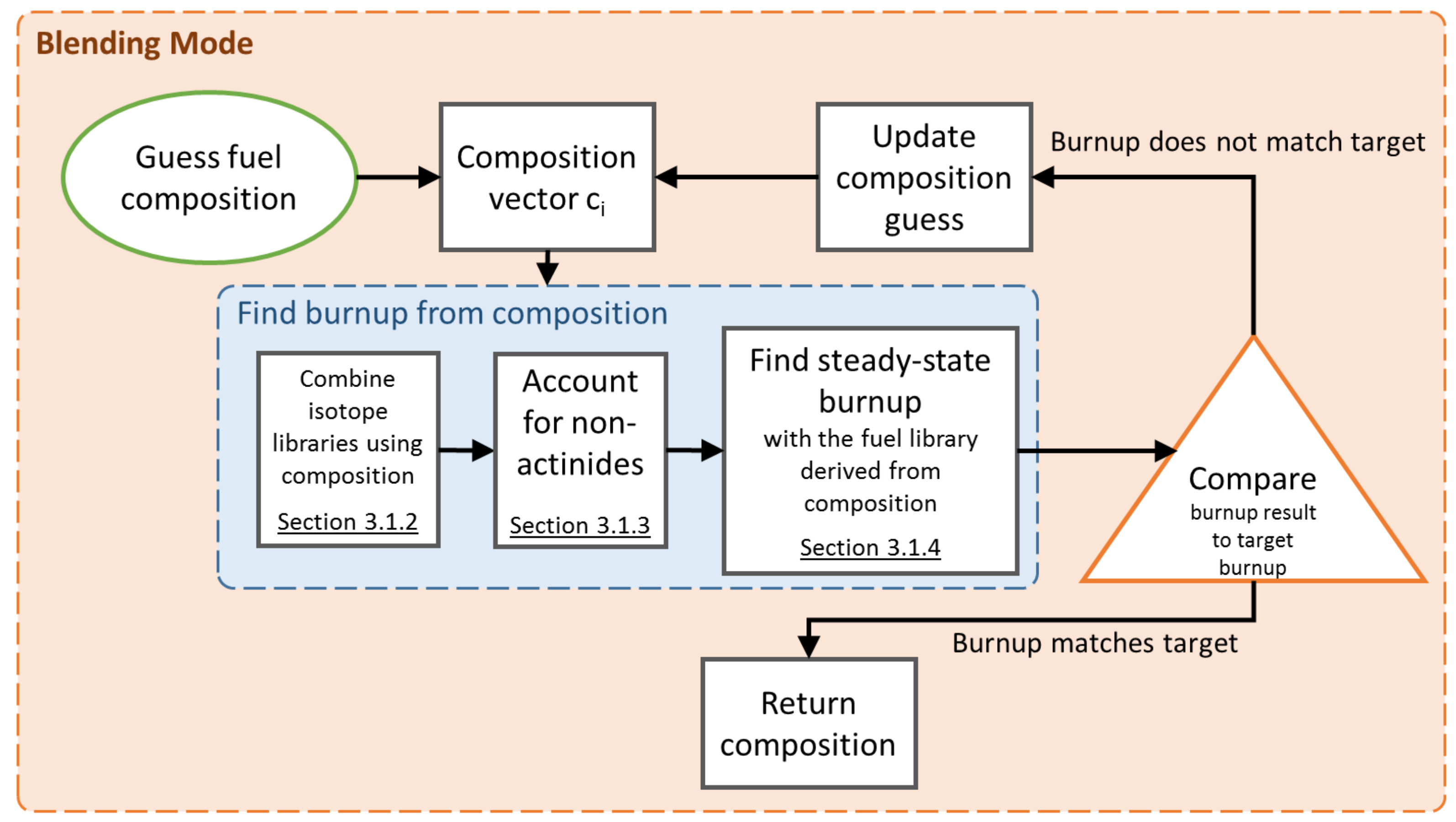
Input Comp
U-235: **??**
U-238: **??**
Th-232: **??**
Pu-239: **??**
…



Output Comp
U-235: **??**
U-238: **??**
Th-232: **??**
Pu-239: **??**
…

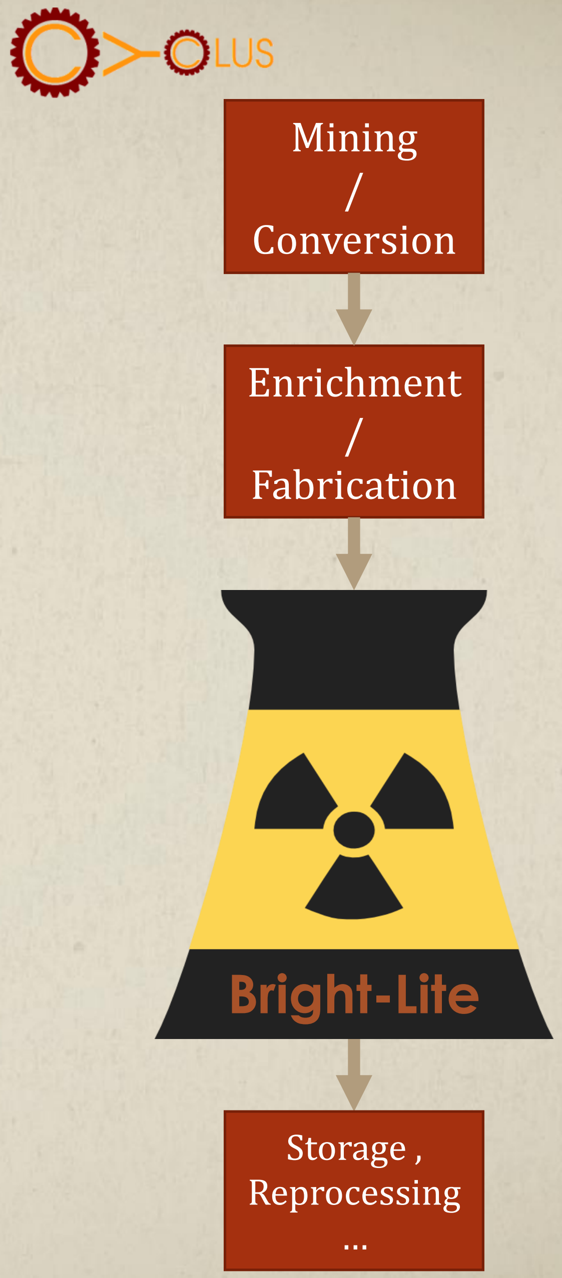
Output Energy
Burnup: **B**

BLENDING MODE – BURNUP TARGET



CHARACTERIZING THE US FLEET

BRIGHT-LITE USED TO SIMULATE THE US NUCLEAR REACTOR FLEET FROM EARLY 1960S UNTIL 2012



DATA TAKEN FROM EIA

Data used in the study was accessed through the **U.S. Energy Information Administration (EIA)** [3][4][5]. **For each reactor** the following information was used:

Startup date

Scheduled shut down date

Lifetime extension data

Time dependent burnup

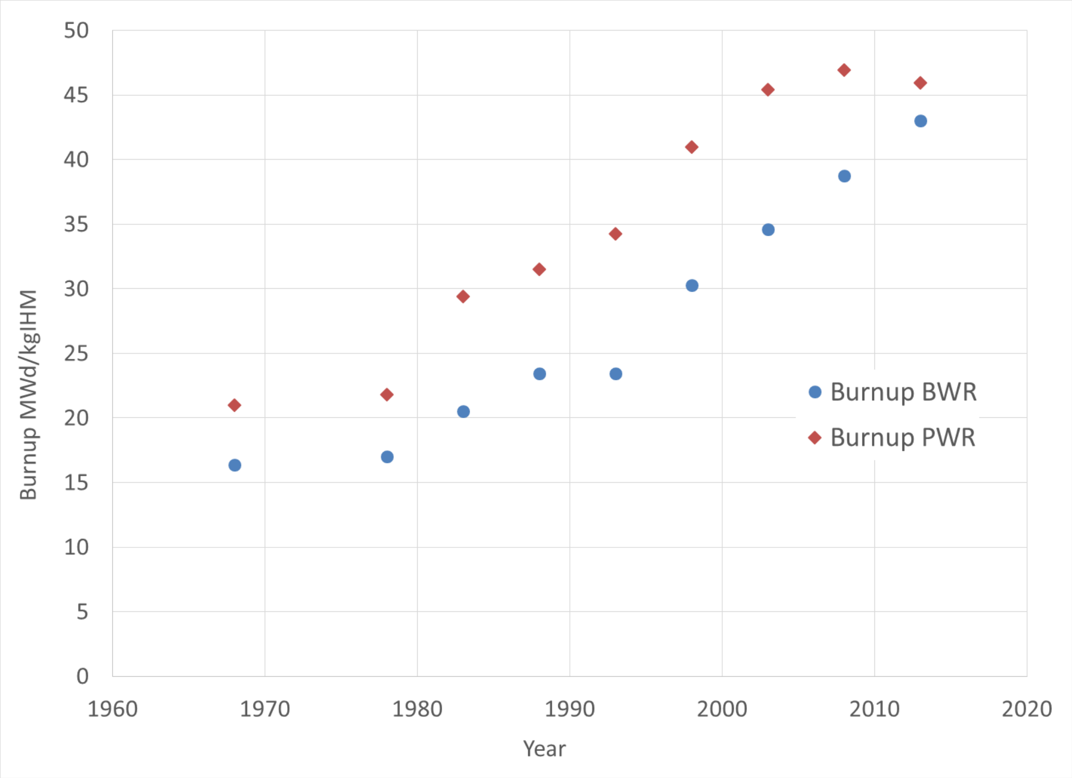
Time dependent availability

Reactor thermal power

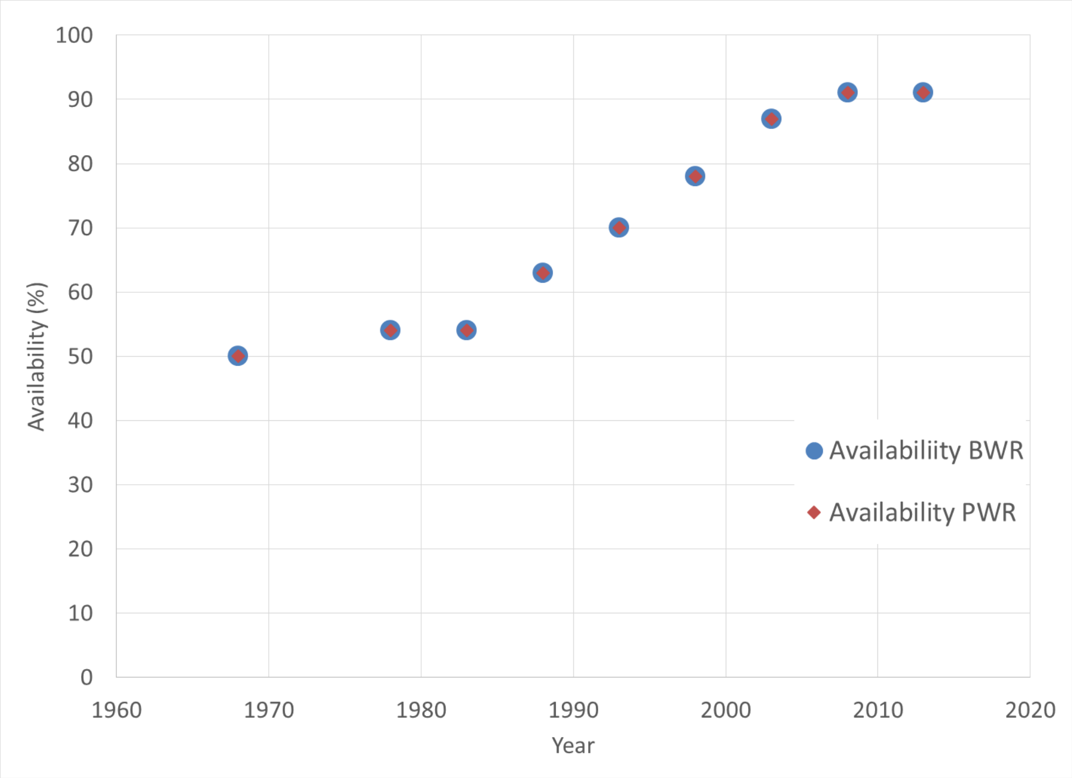
Reactor core mass

DATA TAKEN FROM EIA

Historical **burnups** for the US nuclear fleet



Historical **availability** of the US nuclear fleet

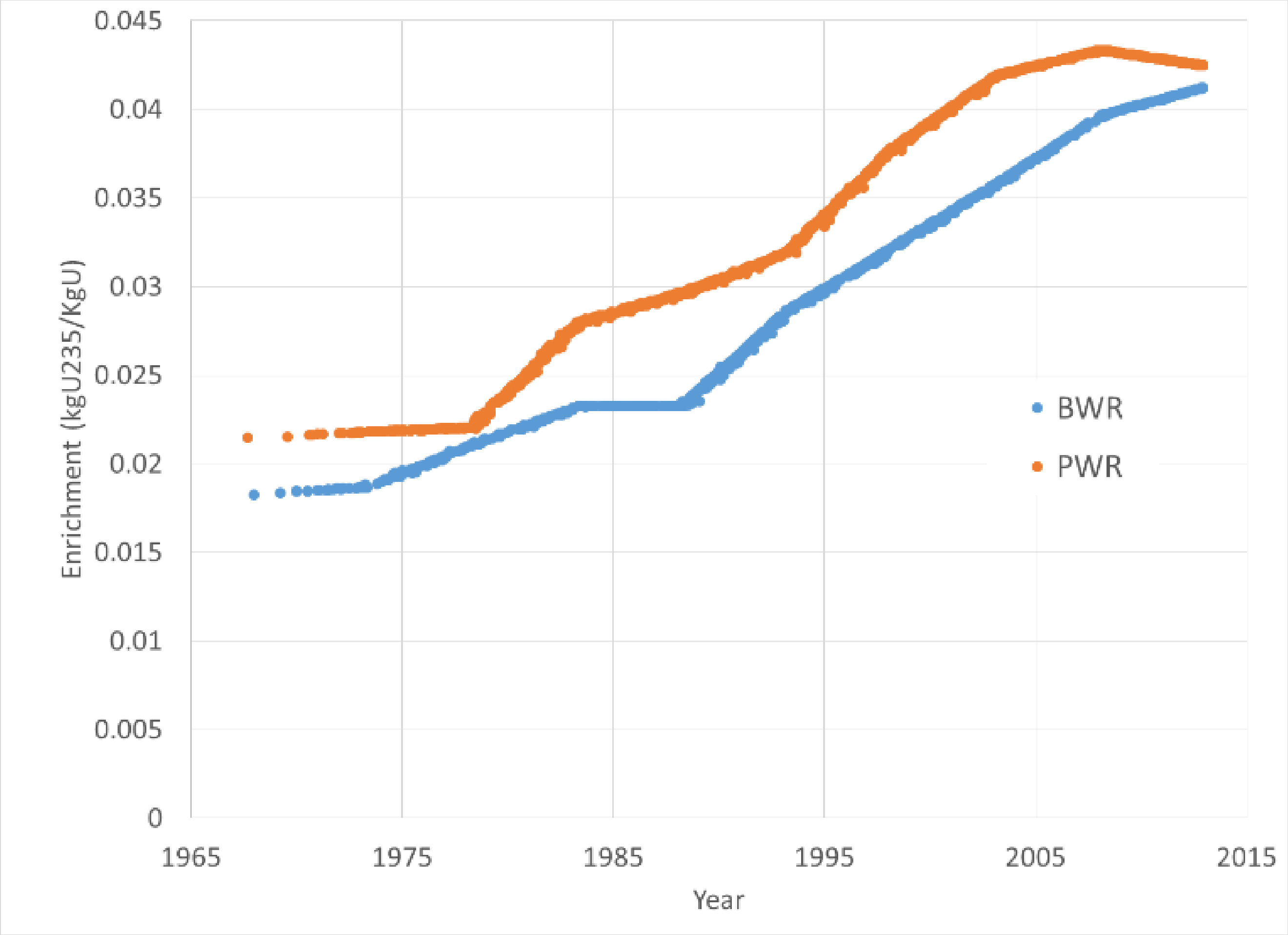


US FUEL CYCLE IN CYCLUS

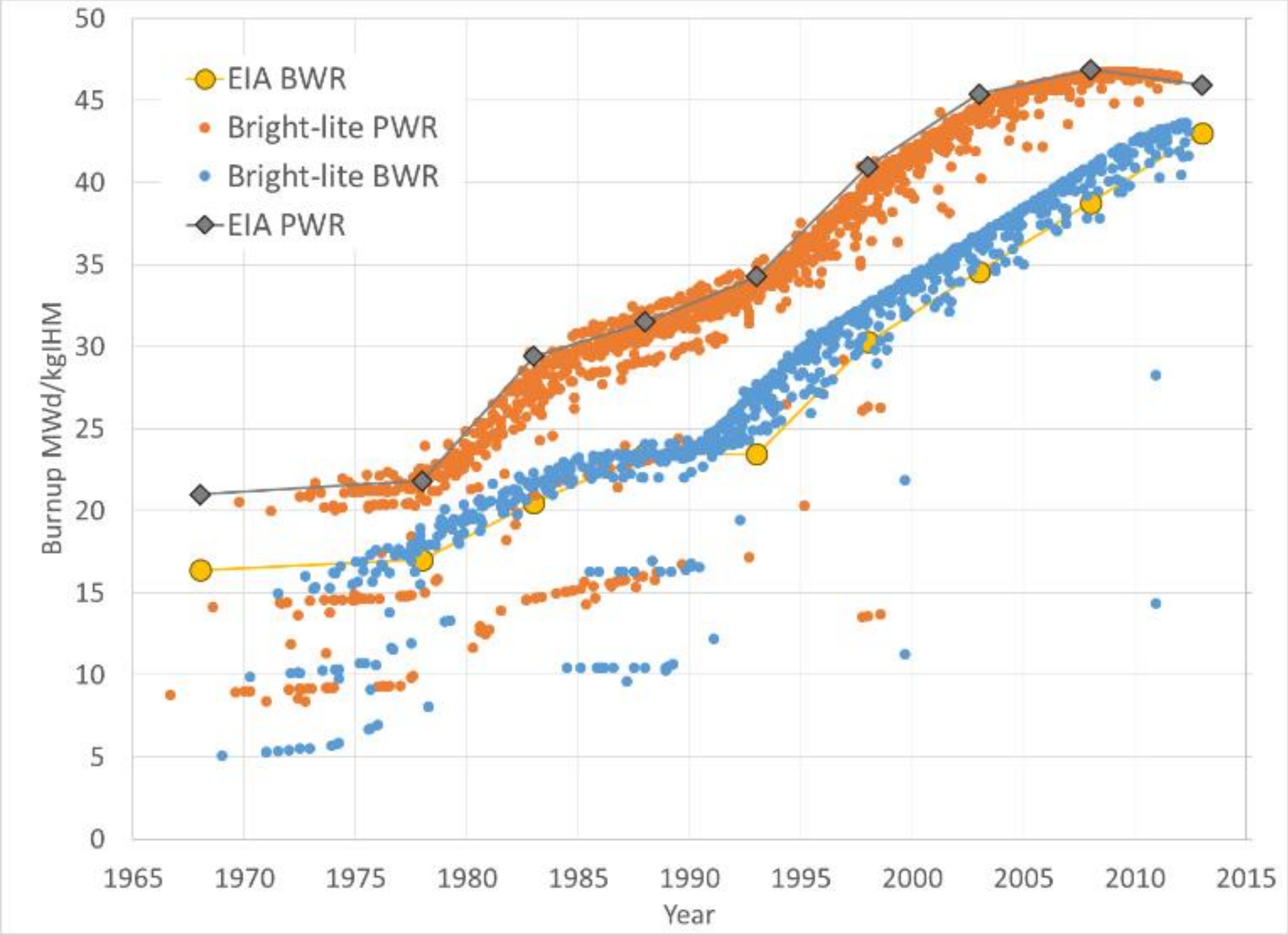
- **Each reactor was represented separately in Cyclus**
- **Reactors calculate the input fuel enrichment based on their burnup target at each refueling**
  - Since the data contains some year-to-year volatility, the burnups were averaged over 5-year intervals to provide the data series used by Bright-lite
  - The fuel enrichments calculated by Bright-lite yield the desired burnup at the equilibrium cycle
- **Bright-lite uses availability data to adjust the outage time of reactors**
  - Instead of introducing arbitrary mid-cycle outages, Bright-lite simply adjusts the refueling outage times such that the trend in long-run average availability is correct

CALCULATED FUEL ENRICHMENTS

- PWR fuel enrichment is consistently higher than BWR enrichments
- Enrichment follows the increasing burnup trend
- Unfortunately, the reference does not provide enrichment data for comparison



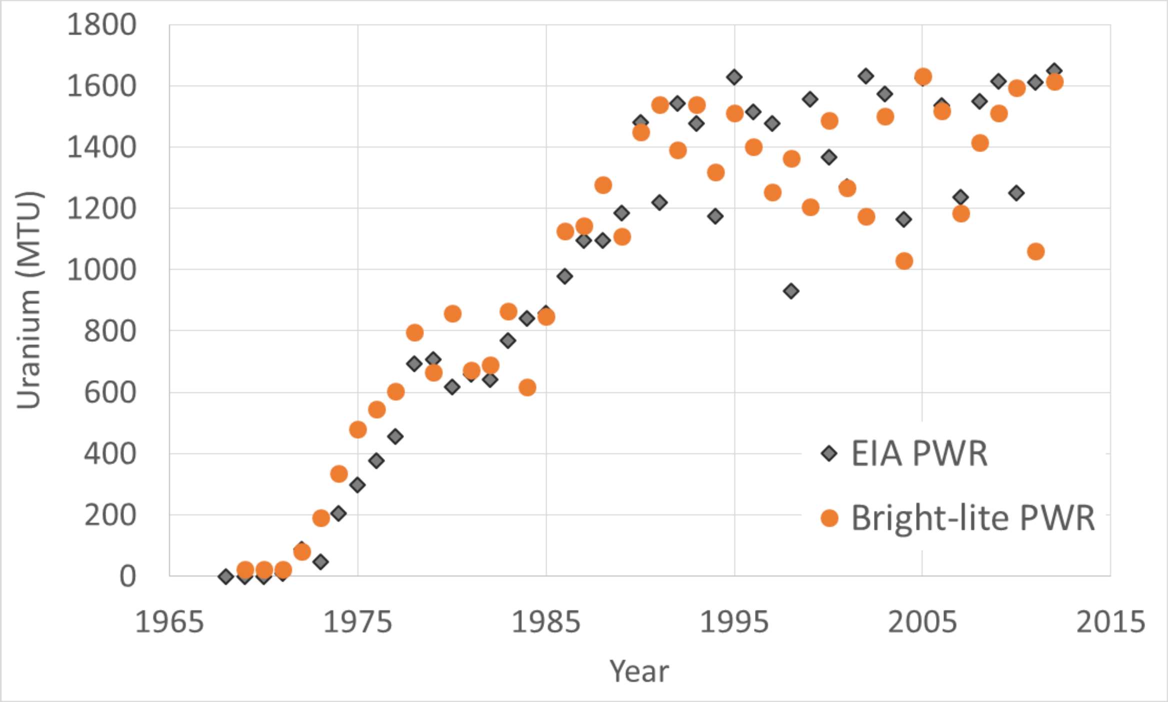
DISCHARGE BURNUP COMPARISON



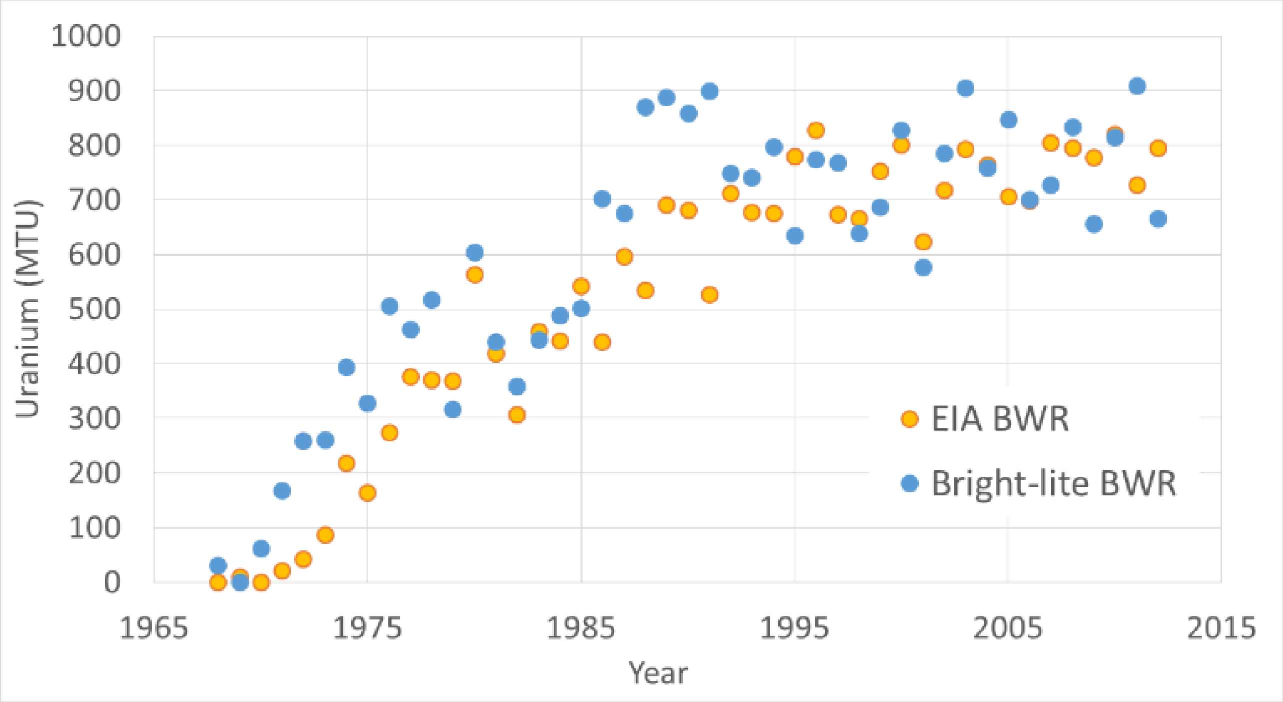
- Figure shows
  - Bright-lite PWR and BWR discharge burnup data by fuel batch
  - EIA PWR and BWR discharge burnup per reactor type
- The low burnup batches are startup batches that reside in core for fewer cycles

TOTAL URANIUM DISCHARGE PER YEAR

PWR's

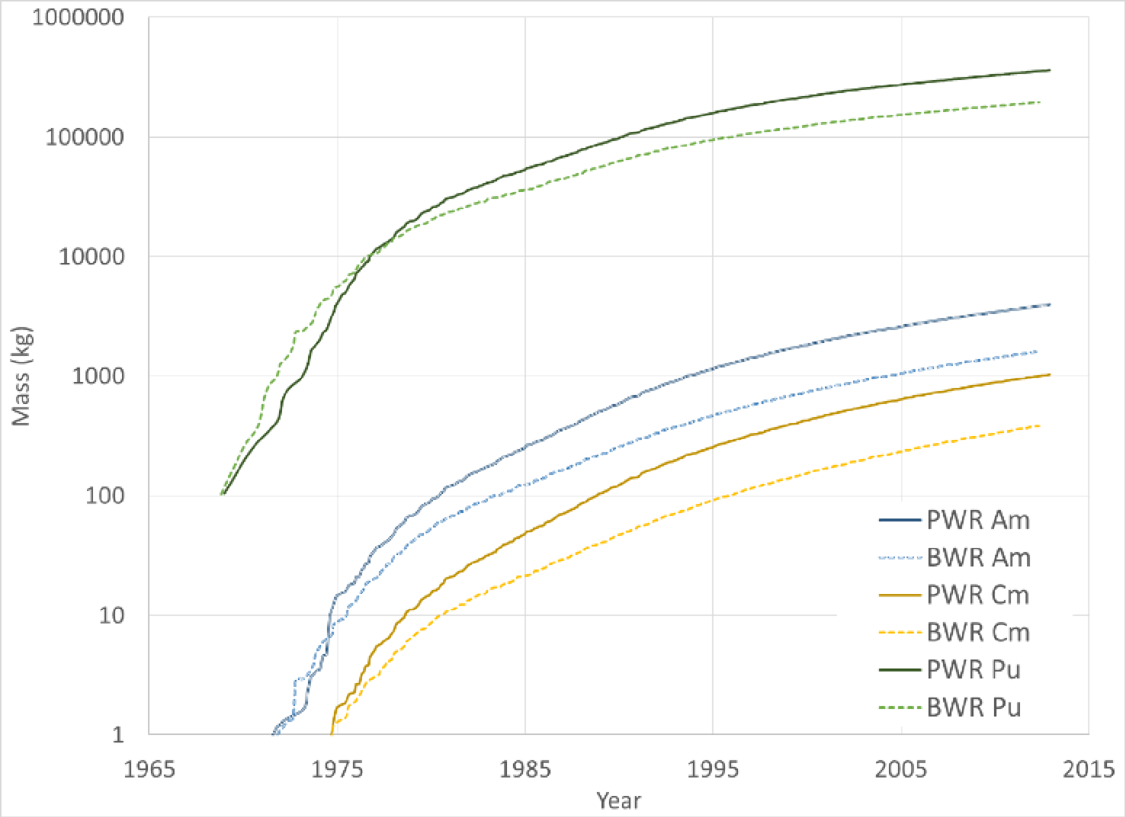


BWR's

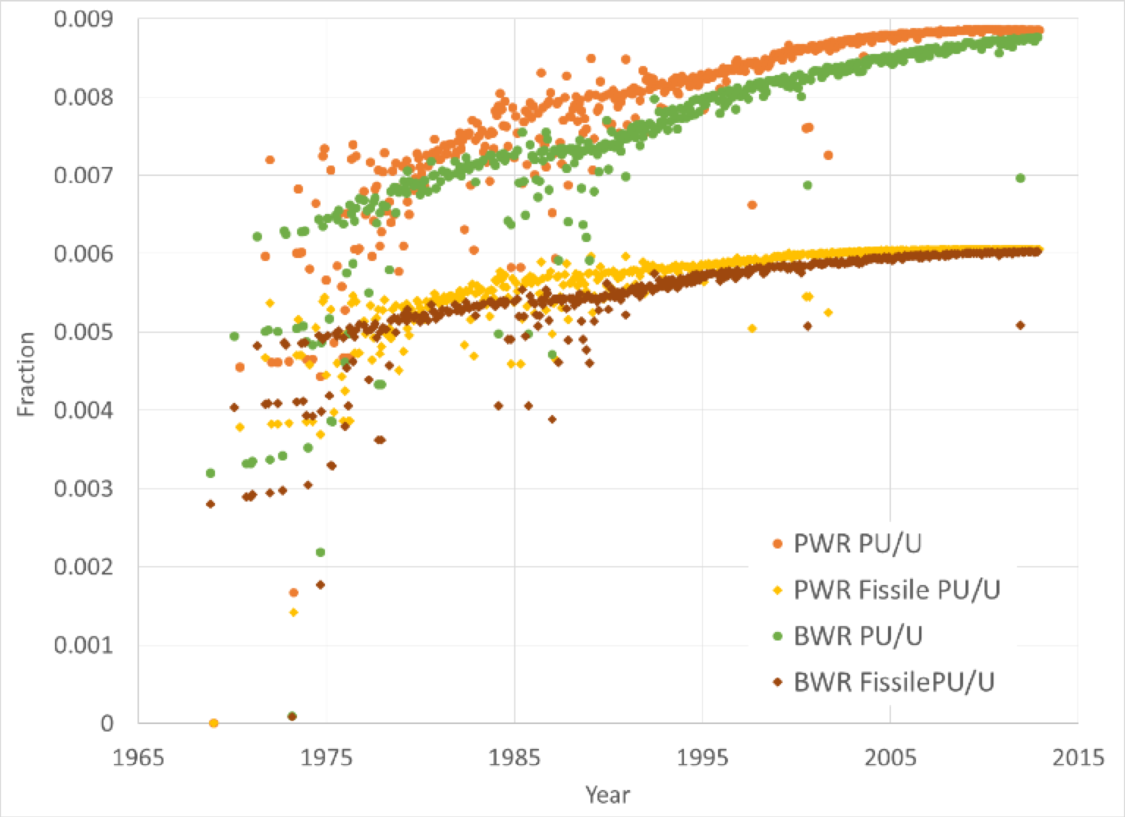


DISCHARGE COMPOSITIONS FROM BRIGHT-LITE

Total mass of Am, Cm, and Pu



Pu and fissile Pu fractions over time



CONCLUSIONS

Bright-lite was used to simulate the US nuclear reactor fleet from the first reactors (early 1960s) until 2012. Discharge burnup data, grouped for BWRs and PWRs, was used to determine a target burnup for each reactor at every refueling

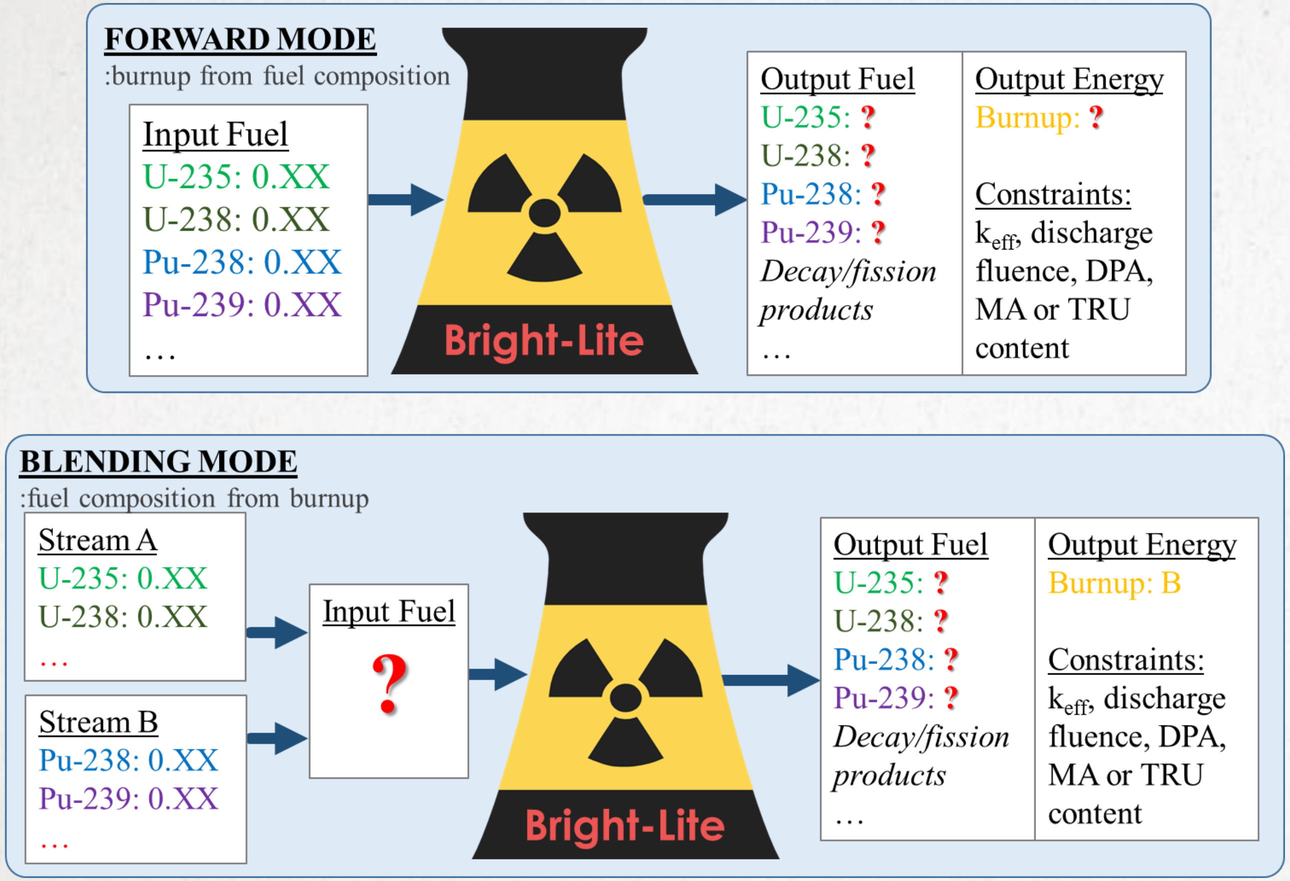
- The study demonstrates Bright-lite's ability to provide **medium fidelity modeling** of reactor operation within a fuel cycle simulator
- Bright-lite's ability to **dynamically determine input fuel compositions** from available feed streams which arise during the simulation allows it to accurately model changing scenarios
- Burnup trends and discharge material masses were shown to closely match the reference data. This qualitative comparison indicates good matching between Bright-lite and the actual data.

FUTURE WORK

- Acquire data on the isotopic discharge vectors for the historical U.S. fleet.
- Generation of higher fidelity pre-computed libraries for Bright-lite
  - Burnup dependent cross-sections
  - Input dependent library interpolation

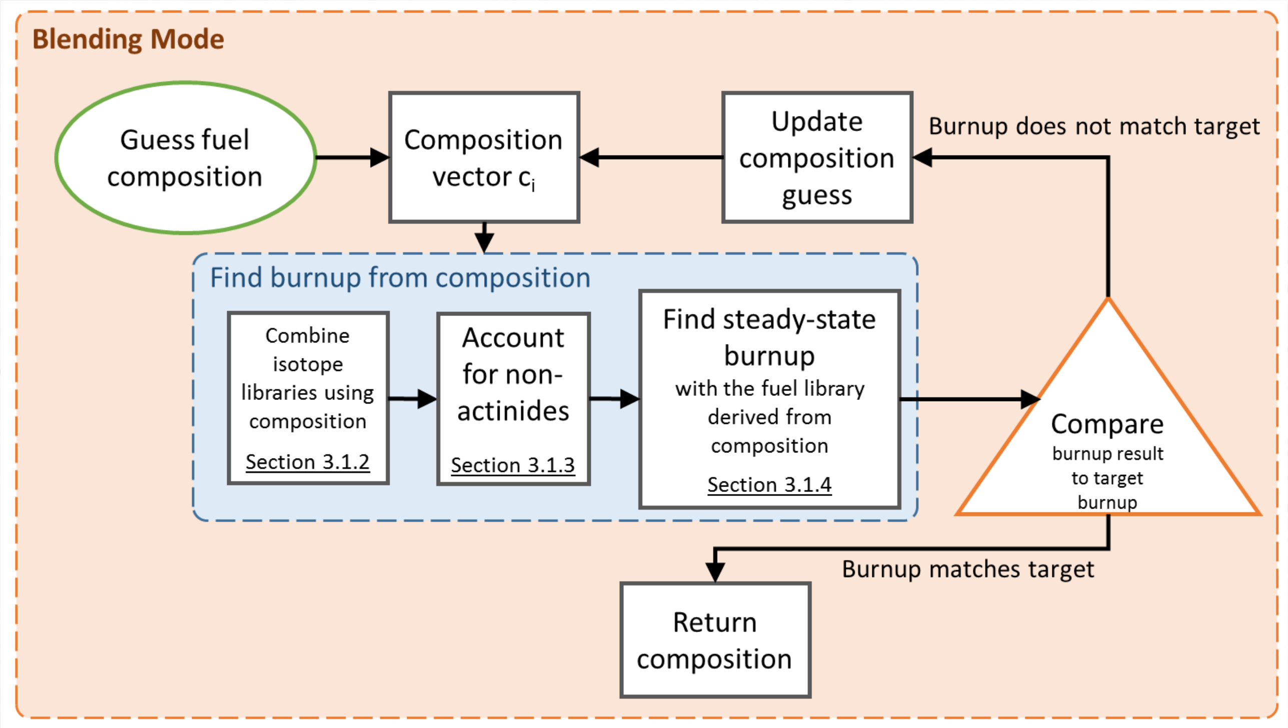
REFERENCES

1) CNERG Fuel Cycle Group, "Cyclus," 01 01 2014. [Online]. Available: http://fuelcycle.org/. Web. 01 Jan. 2014.
2) "Fuel Composition Calculation Techniques of Nuclear Fuel Cycle Simulators," PHYSOR 2014, The Westin Miyako, Kyoto, Japan, 28 Sep. – 03 Oct. 2014, on CD-ROM (2014)
3) "Table 3. Nuclear Reactor Characteristics and Operational History" *Nuclear & Uranium*. U.S. Energy Information Administration, 11 Nov. 2011. Web. 14 Dec. 2015.
4) "Table 1. Nuclear Reactor, State, Type, Net Capacity, Generation and Capacity Factor" *Nuclear & Uranium*. U.S. Energy Information Administration, 11 Nov. 2011. Web. 14 Dec. 2015.
5) "Table 3. Annual Commercial Spent Fuel Discharges and Burnup, 1968- June 30, 2013" *Spent Nuclear Fuel*. U.S. Energy Information Administration, Dec. 7 2015. Web. 14 Dec. 2015.
6) "Multidimensional Cross Section Library Interpolation for the Bright-lite Reactor Modeling Software," Robert Flanagan, E. Schneider, C. Bagdatlioglu; Global, 2015.
7) "Standard- and Extended-Burnup PWR and BWR reactor models for the ORIGEN2 Computer Code" S.B. Ludwig, J.P. Renier, Oak Ridge National Laboratory, Jan 3, 1990.
8) "Using Spatial Flux Calculations to Improve the Fluence-Based Neutron Balance Approach," Cem Bagdatlioglu, Erich Schneider, Robert Flanagan; ANS Annual 2015.



ADDITIONAL INFORMATION

Two Modes of operation for Bright-lite

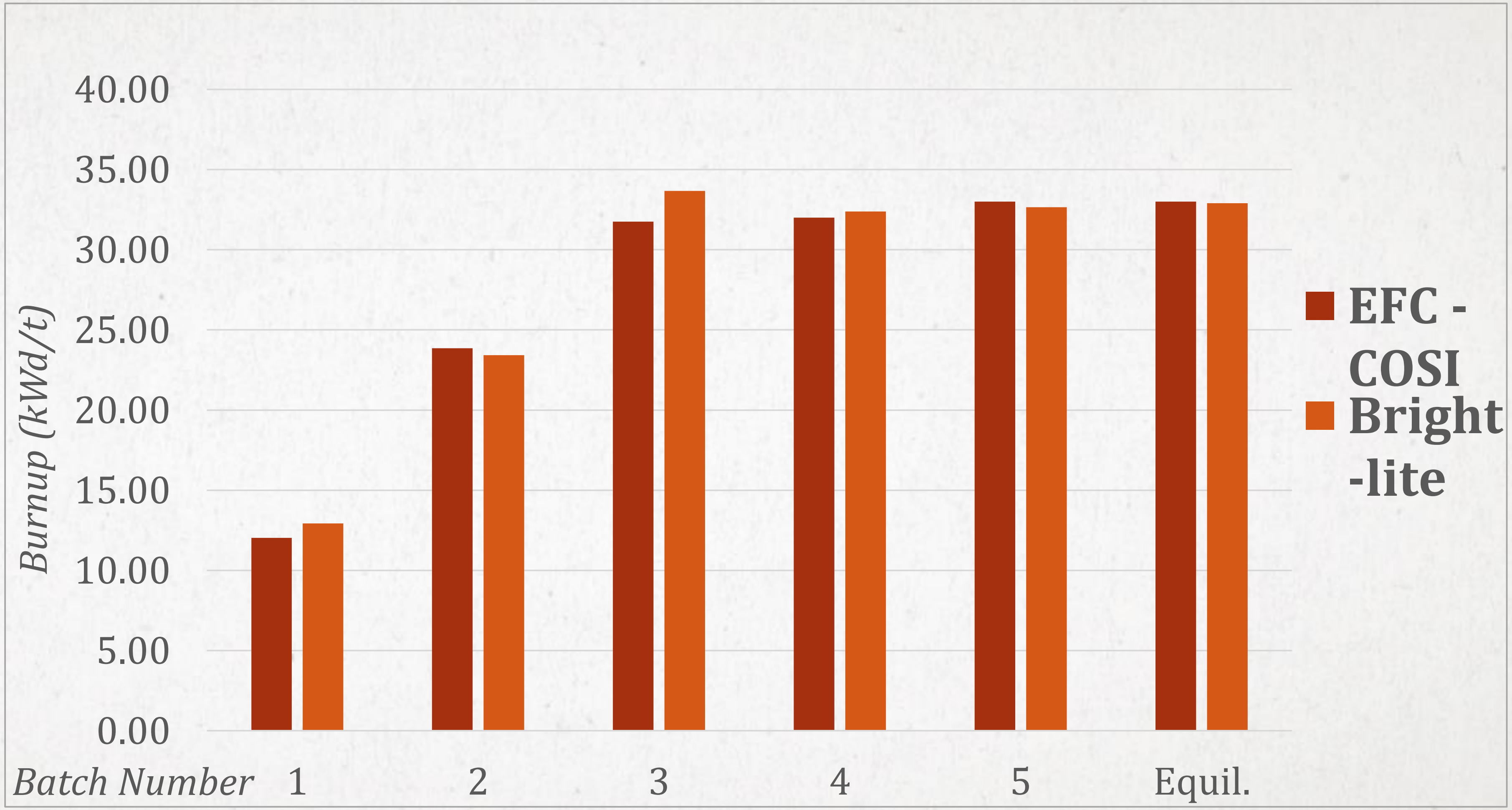


ADDITIONAL INFORMATION

Blending mode

Bright-lite Benchmarks – EFC 33

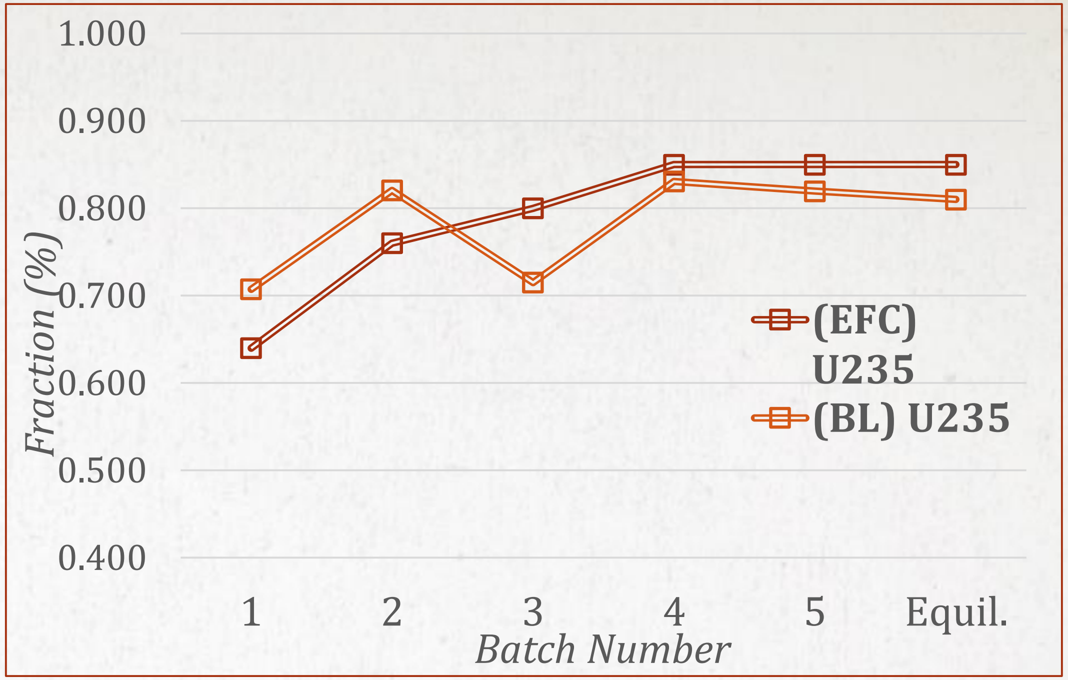
Initial loading	
Batch	**Enrichment(%)**
1	1.500
2	2.400
3	2.950
n>3	3.100

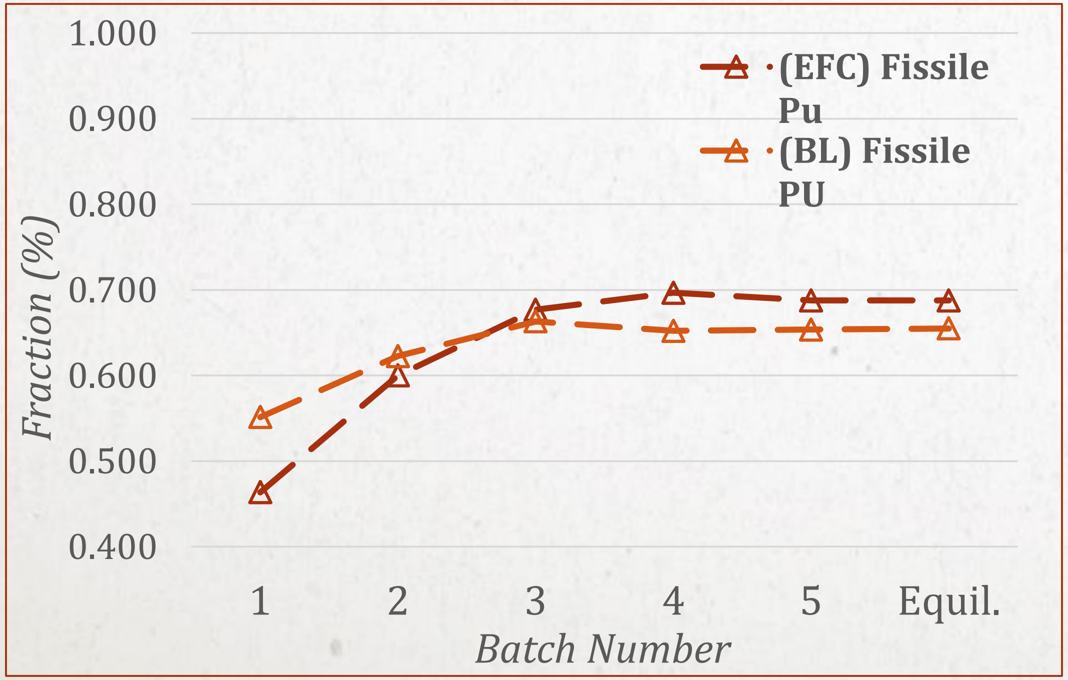


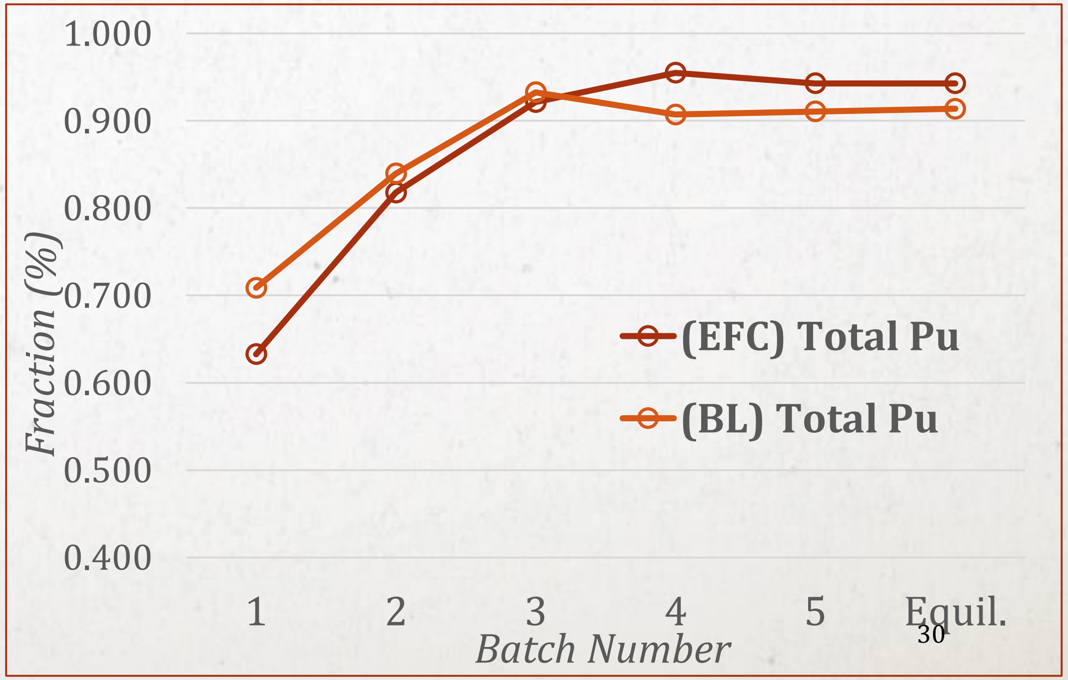
Error (%)	7.39	1.85	6.02	1.19	1.04	0.31

Bright-lite Benchmarks – EFC 33

Initial loading	
Batch	**Enrichment(%)**
1	1.500
2	2.400
3	2.950
n>3	3.100

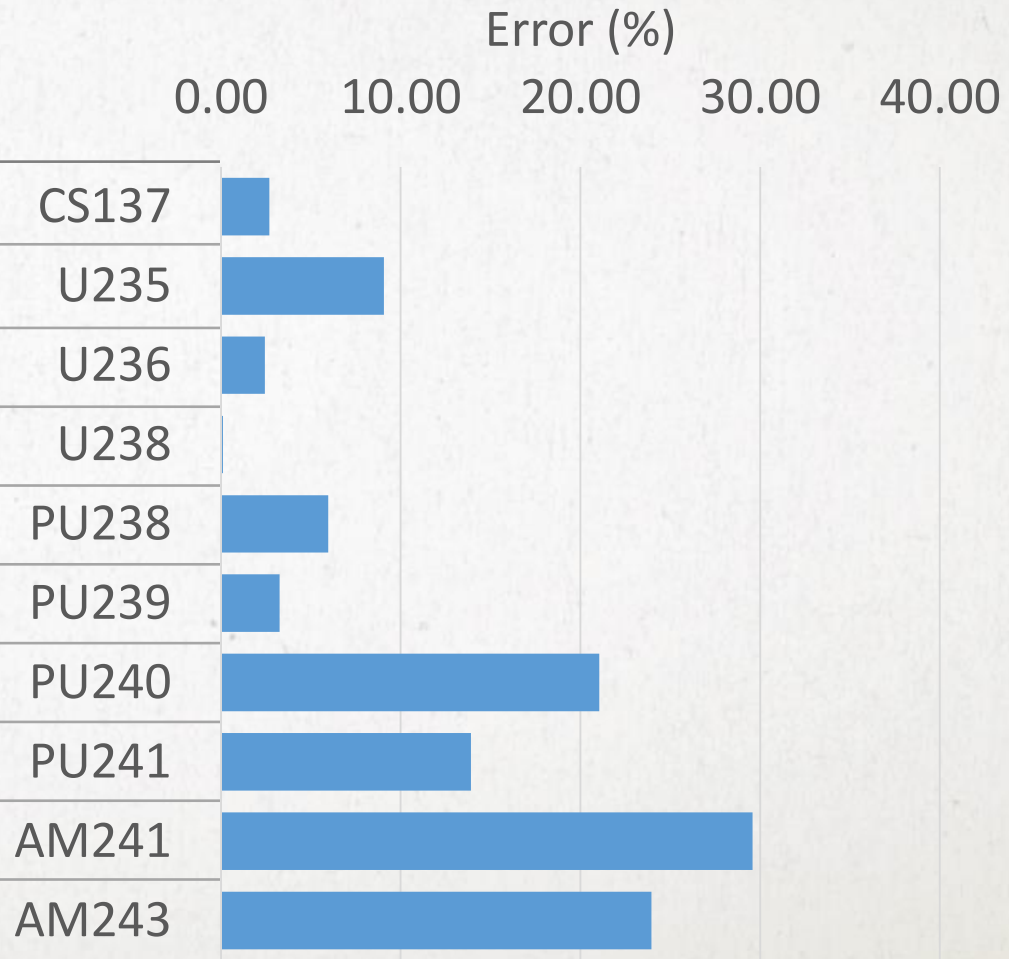






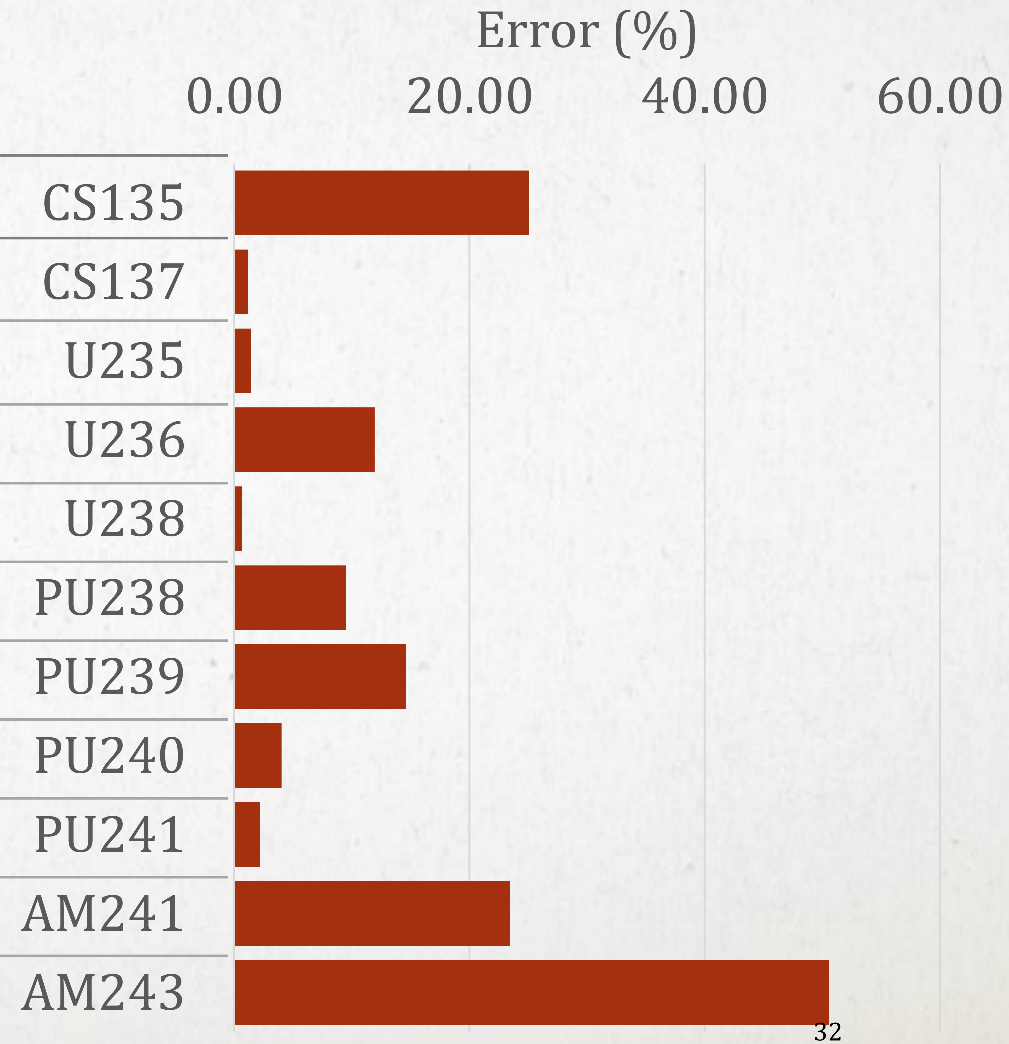
Bright-lite Benchmarks – LWR VISION 51

	VISION	Bright-lite	Error (%)
Enrichment	0.043*	0.043 (input)	
Equil. Burnup	51 (input)	50.02	1.92
Equilibrium Output Composition (%)			
CS137	0.182	0.177	2.69
U235	0.765	0.834	9.07
U236	0.571	0.557	2.45
U238	92.10	92.20	0.11
PU238	0.0293	0.0310	5.97
PU239	0.615	0.595	3.27
PU240	0.291	0.230	21.06
PU241	0.176	0.200	13.91
AM241	0.00644	0.00835	29.58
AM243	0.020	0.025	23.95



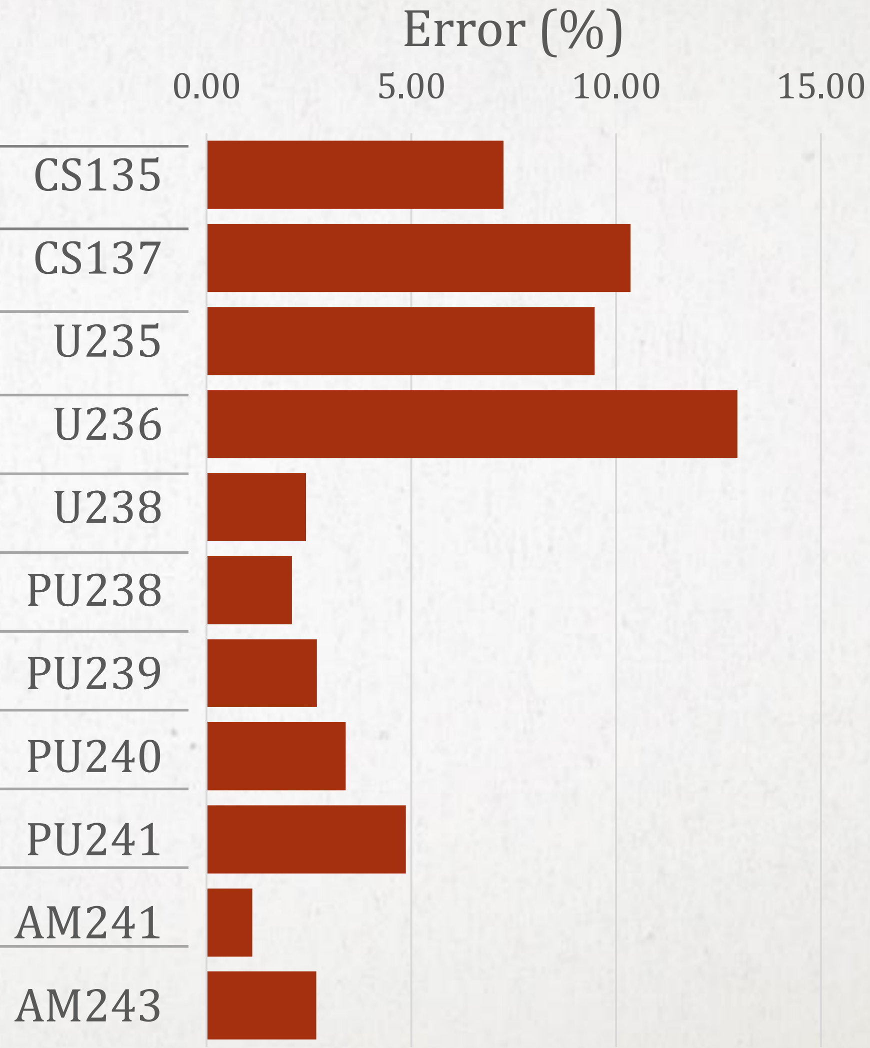
Bright-lite Benchmarks – VISION MOX-NU-Pu

	VISION	Bright-lite	Error (%)
Enrichment	0.043*	0.043 (input)	
Equil. Burnup	51 (input)	50.02	1.92
Equilibrium Output Composition (%)			
CS135	1.49E-03	1.11E-03	25.05
CS137	1.87E-03	1.85E-03	1.17
U235	1.20E-03	1.21E-03	1.40
U236	2.57E-04	2.27E-04	11.95
U238	8.67E-01	8.73E-01	0.64
PU238	2.34E-03	2.12E-03	9.53
PU239	2.90E-02	2.48E-02	14.58
PU240	2.28E-02	2.19E-02	4.01
PU241	1.22E-02	1.25E-02	2.20
AM241	1.34E-03	1.03E-03	23.43
AM243	2.09E-03	3.14E-03	50.55

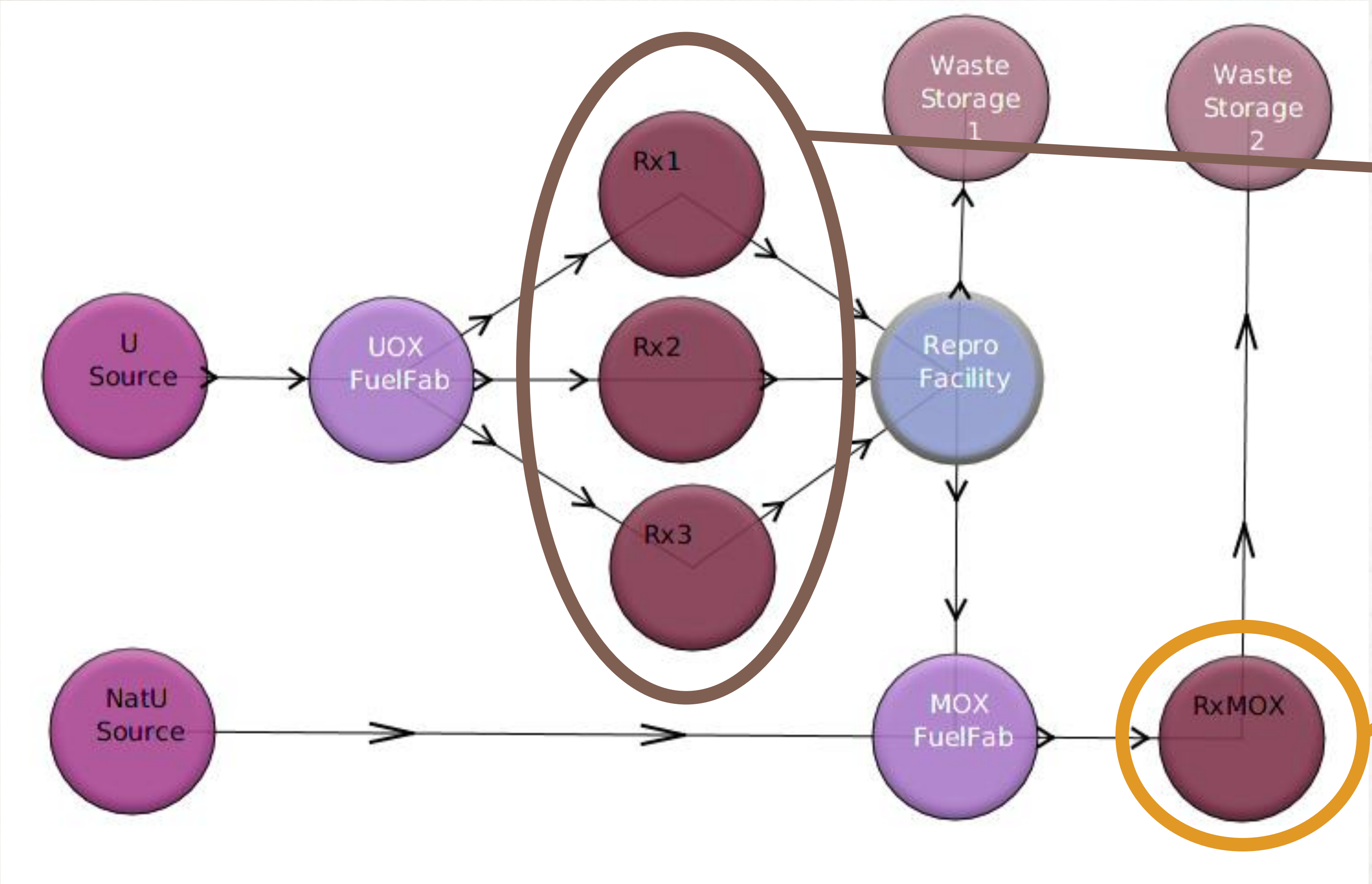


Bright-lite Benchmarks – VISION Fast Reactor (UOX to FR-mtl-0.25)

	VISION	Bright-lite	Error (%)
Equil. Burnup	185.6	188.9	1.78
Equilibrium Output Composition			
CS135	8.383E-03	7.775E-03	7.25
CS137	7.383E-03	6.619E-03	10.35
U235	4.429E-04	4.849E-04	9.48
U236	1.777E-04	1.547E-04	12.97
U238	4.748E-01	4.863E-01	2.43
PU238	1.419E-02	1.390E-02	2.09
PU239	1.247E-01	1.280E-01	2.70
PU240	9.458E-02	9.136E-02	3.40
PU241	2.281E-02	2.392E-02	4.87
AM241	1.137E-02	1.150E-02	1.12
AM243	7.333E-03	7.136E-03	2.68



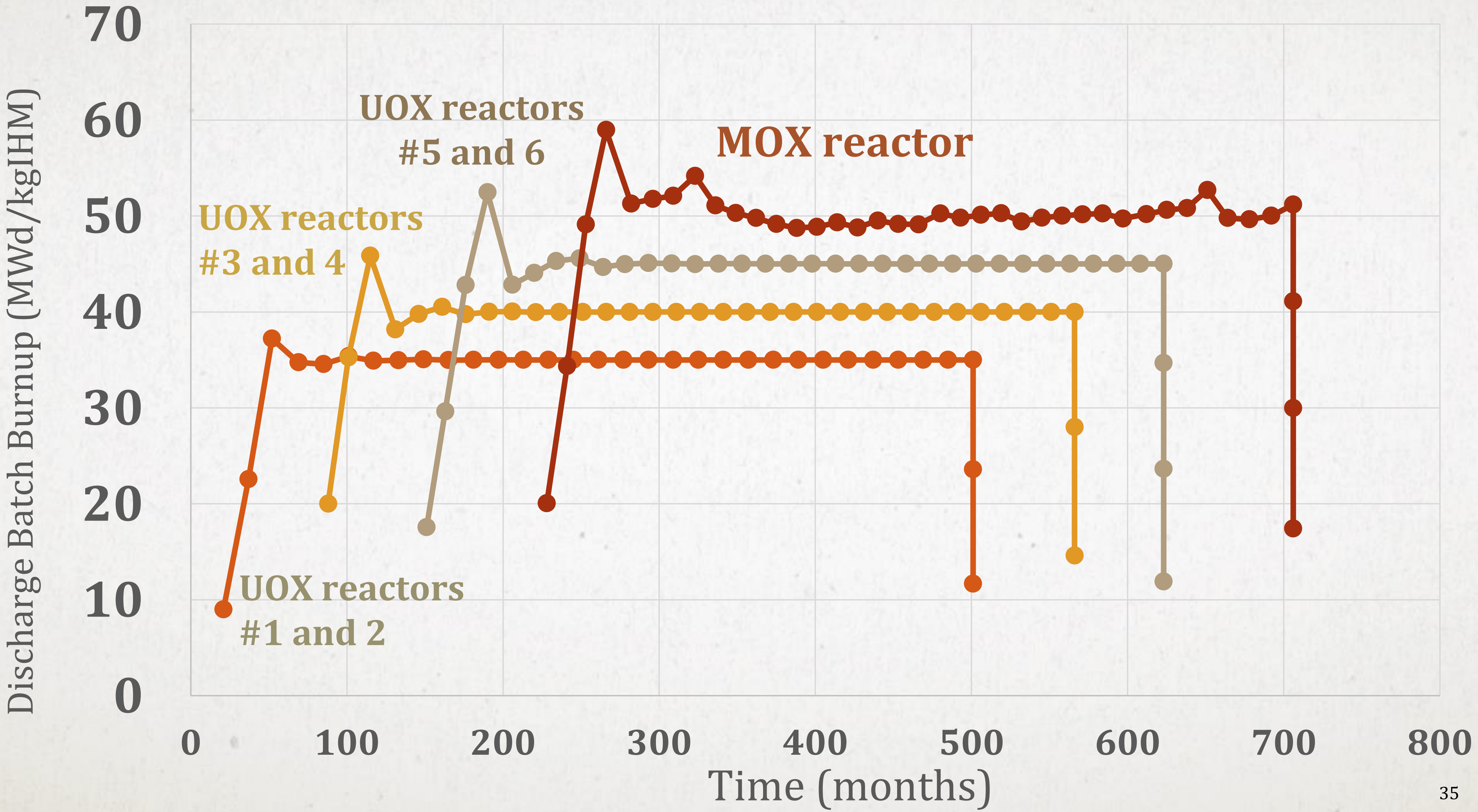
TRANSIENT MOX SCENARIO USING BRIGHT-LITE AND CYCLUS



6 UOX fueled LWRs (two each w/ equil burnups of 35, 40, 45 MWd/kg) come online over 10 years
All reactors have 40 year lifetimes

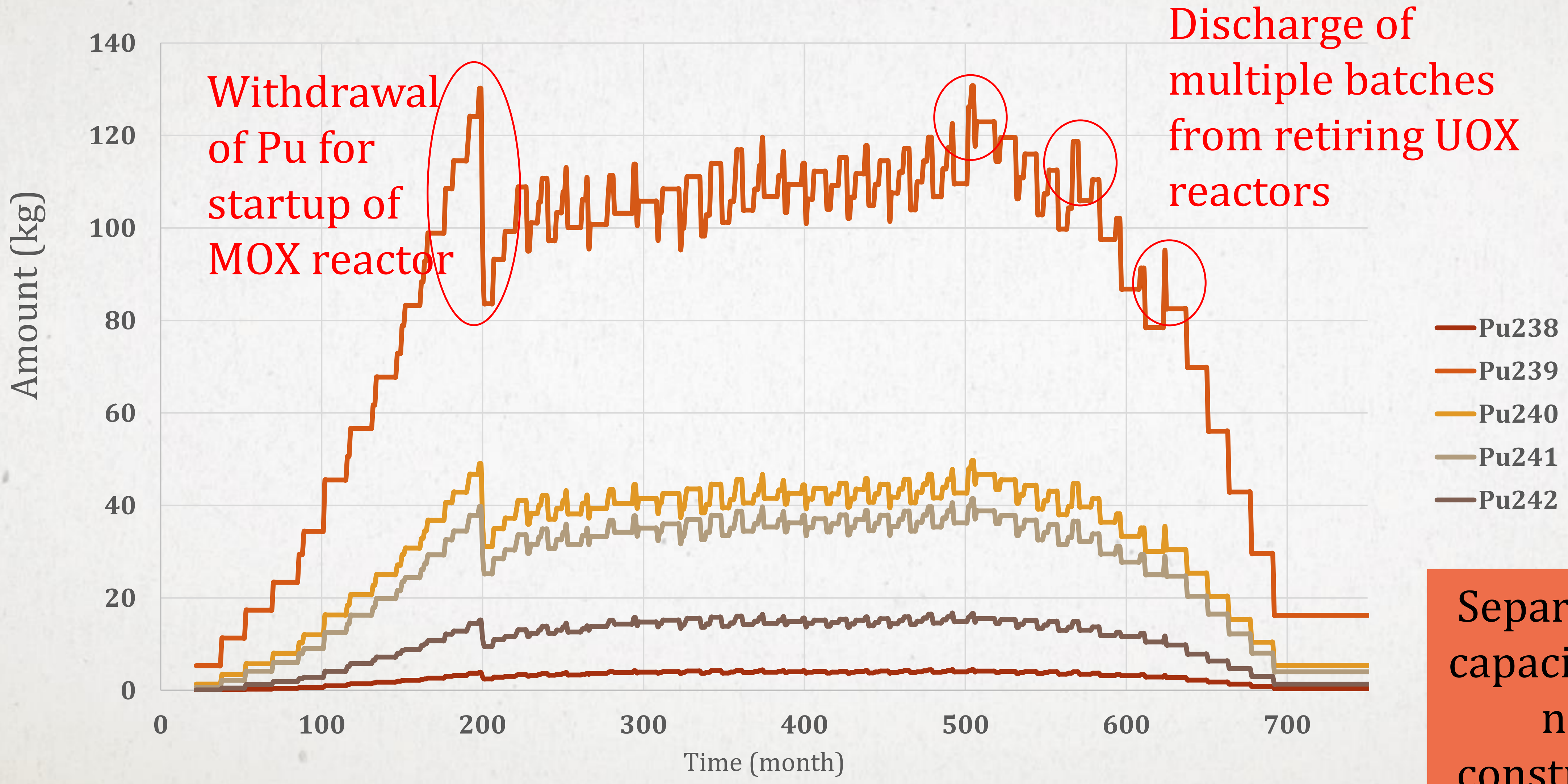
One MOX reactor (equil burnup of 50 MWd/kg) comes online 17 years after start of simulation
Uses Pu from LWRs

DISCHARGE BURNUPS OF EACH BATCH IN SIMULATION



MOX REACTOR INPUT PLUTONIUM CONTENT & ISOTOPICS BY BATCH

INVENTORY OF PLUTONIUM IN UOX USED FUEL PLUS PLUTONIUM REPROCESSED BUT NOT YET RECYCLED



Separations capacity was not constrained