

Interpolating Fuel Cycle Behavior for Scenario Analysis Codes: Thermal IMF Recycle

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Outline

- Scenario Analysis Codes
- Methodology
- Inert Matrix Fuel (IMF) Material Description
- Assembly Geometry
- IMF Cycle Description
- Initial Interpolation Scheme
- Revised Interpolations Scheme
- Conclusions



Scenario Analysis Codes

- DANESS (ANL)
- VISION (INL)
- Model mass flows throughout entire fuel cycle
- Use STELLA and Powersim software

DANESS *Dynamic Analysis of Nuclear Energy System Strategies*
v2.0 r1

August 2006

Menu

- Model Parameters
- Reactor TRL Data
- Facility TRL Data
- Learning Effect Coefficients
- Economic Data
- Government Parameters
- Utility Finances

Choose Energy Demand

- Edem Scenario
- Rest-of-World

Reactor

- Reactor Data
- Reactor Park Decision Making
- Reactor & Fuel Combination

Fuel Cycle

- Initial Stocks
- Unit Resources
- Unit Price
- Fuel Data
- Fuel & Fuel Facility Combinations
- Fuel Cycle Facility Data
- Facility Deployment
- Existing Facility Shutdown
- Reprocessing Fractions
- Cooling Times per Fuel
- Separated Actinide Allocation
- Priorities for Conditioning and Reprocessing

Analysis of Results

- Analysis of Results
- Initial Stocks in 2000

Case ID 1

Results

- Summary Graph
- Summary Output
- Indicators Graph
- Indicators Output
- Energy and Capacity
- Front End
- Back End
- Recycling
- Waste
- SF HLW
- Economics
- Decay Heat Disposal
- Facilities
- Energy and Capacity
- Front End
- Back End
- Recycling
- Waste
- SF HLW
- Economics
- Decay Heat Disposal
- Facilities

Run 2100.00
Import Case-Settings
Export Settings and Results
Case Settings
Analysis of Results
Initial Stocks in 2000

Save Settings in New File
Quit DANESS

Verifiable Fuel Cycle Simulation Model (VISION)

Year: 2040, 2060, 2080, 2100

Run base case? No Yes

PHASE 1 DATE 2010, 2040, 2070, 2100 (2025)

PHASE 2 DATE 2010, 2040, 2070, 2100 (2040)

Phase 1 **Phase 2**

UOX	-	UOX
UOX	-	UOX
UOX	-	MOX PuNp
UOX	-	MOX PuNpAm
UOX	-	IMF PuNp
UOX	-	IMF PuNpAm
UOX	-	IMF PuNpAmCm
UOX	-	FR Burner
UOX	-	FR Breeder

NOTE: Choosing to run a base case will override all manual user input variables, even though user input variables may still be visible and appear to change. ONLY THE PRESET VALUES ARE USED.

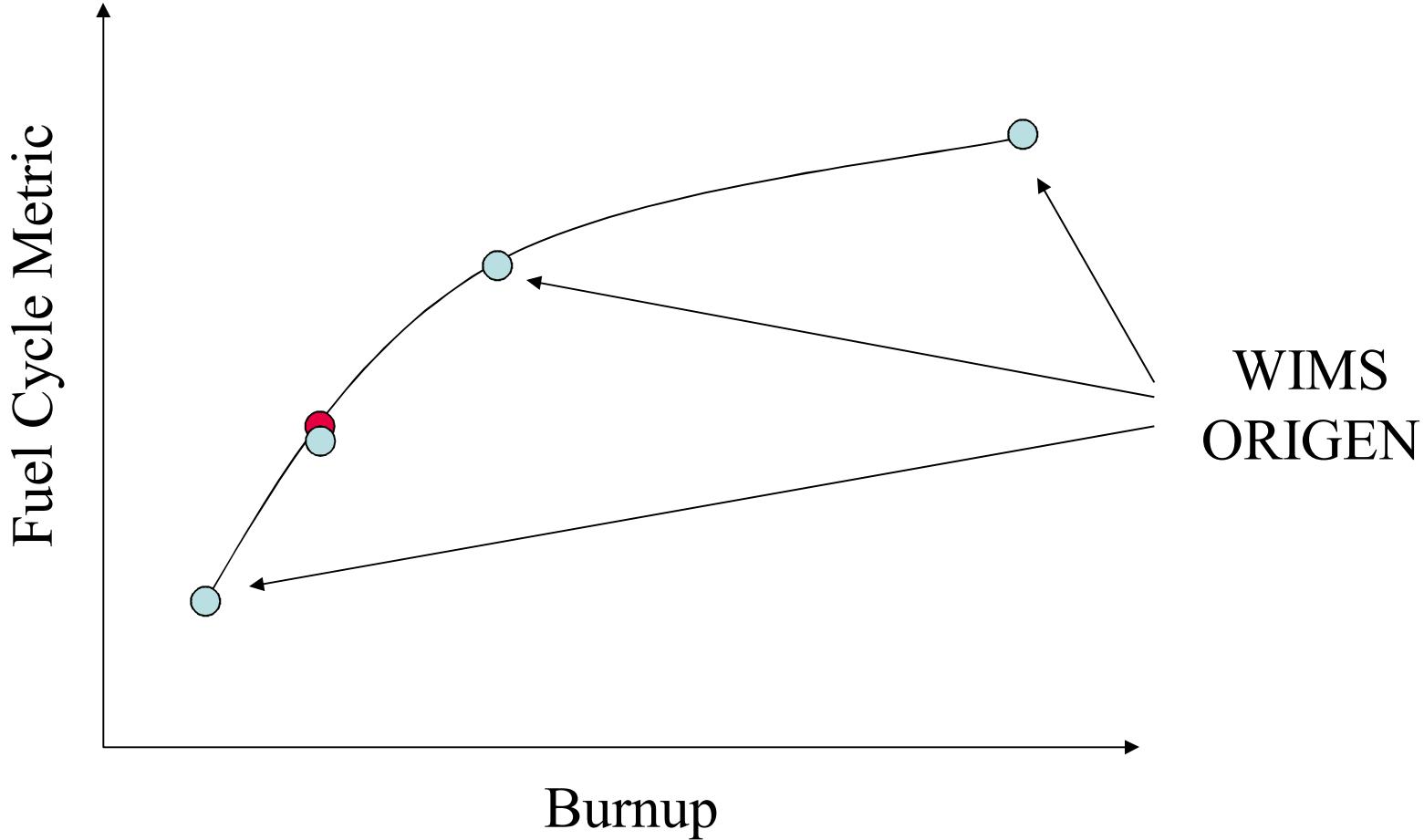


Scenario Analysis Codes (Cont.)

- Accurate mass flows require knowledge of
 - TRUO₂ Mass Fraction
 - Charge Mass
 - Discharge Mass
 - Blending Ratios
 - Charge Vector
 - Discharge Vector
- Performance requirements rule out detailed physics modules
- Therefore, require simplified interpolation equations



Methodology - Overview





Inert Matrix Fuel (IMF)

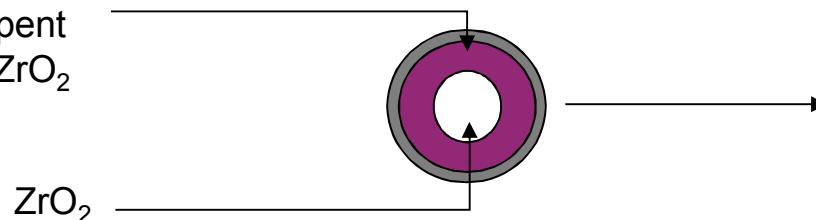
- LWR-IMF system is one of nuclear fuel cycles considered in scenario study under AFCI project of US-DOE
- Pu, Np, and Am extracted from spent nuclear fuel
- Placed in an inert matrix material which is:
 - Neutron transparent
 - Chemically stable
 - Radiation damage resistant
 - Economically reasonable
- Zirconia stabilized by yttrium oxide and combined with spinel to compensate for zirconia matrix's low conductivity



IMF Fuel Assembly Geometry

- Homogeneous Fuel Assemblies
 - IMF fuel pins are located at all fuel pins positions of 17x17 typical PWR assembly
 - IMF fuel pins are made by blending TRUs of previous IMF cycle and LWR spent fuel
 - Blending ratio and TRUO_2 mass fraction are key parameters to maintain a desired cycle length

TRU of previous
IMF cycle, TRU
of LWR spent
fuel, and ZrO_2

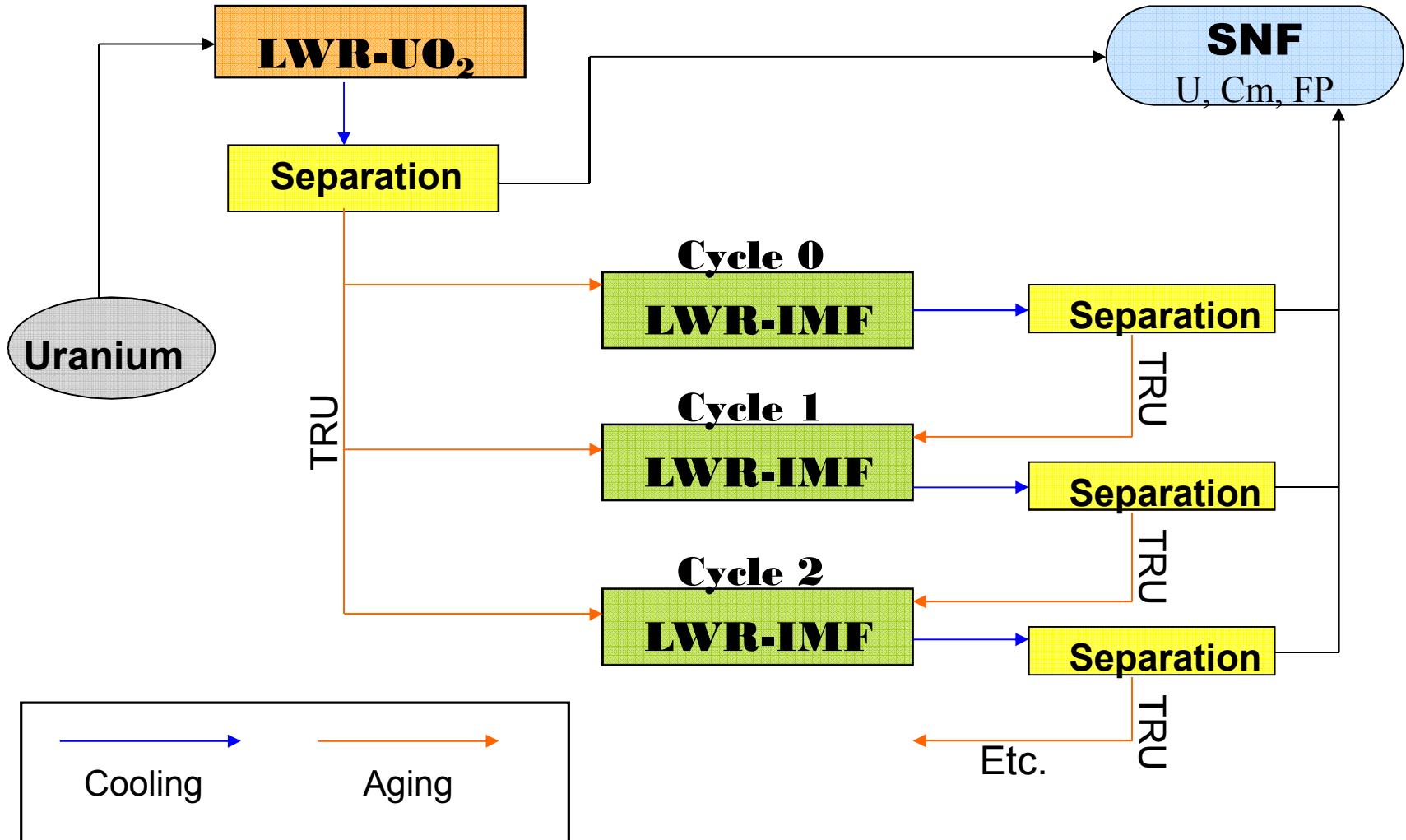


F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
F	F	F	F	G	F	F	G	F	G	F	F	F	F	F	F	F
F	F	F	G	F	F	F	F	F	F	F	F	G	F	F	F	F
F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
F	F	F	F	G	F	F	G	F	G	F	F	G	F	F	G	F
F	F	F	F	F	G	F	F	G	F	G	F	F	G	F	F	F
F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
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F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F

Homogeneous IMF Assembly



IMF Cycle





IMF Calculations

- TRUO₂ mass fraction
- Radius of zirconium center

$$r_{Zr} = -0.0019 * MF_{TRUO} + 0.2453$$

- 95% theoretical density

$$\rho_{IMF_{95}} = \frac{0.95 * V_{ff} \rho_{HMO} \rho_{ZrO}}{[MF_{TRUO} * \rho_{ZrO} + (1 - MF_{TRUO}) * \rho_{HMO}] (1 + D_f)}$$

- Charge mass

$$M_{charge} = MF_{TRUO} MF_{TRU} V_A * \rho_{IMF_{95}}$$

- Discharge mass
- Blending ratio
- Critical burnup

$$B_c = \frac{n+1}{2n} B_d$$



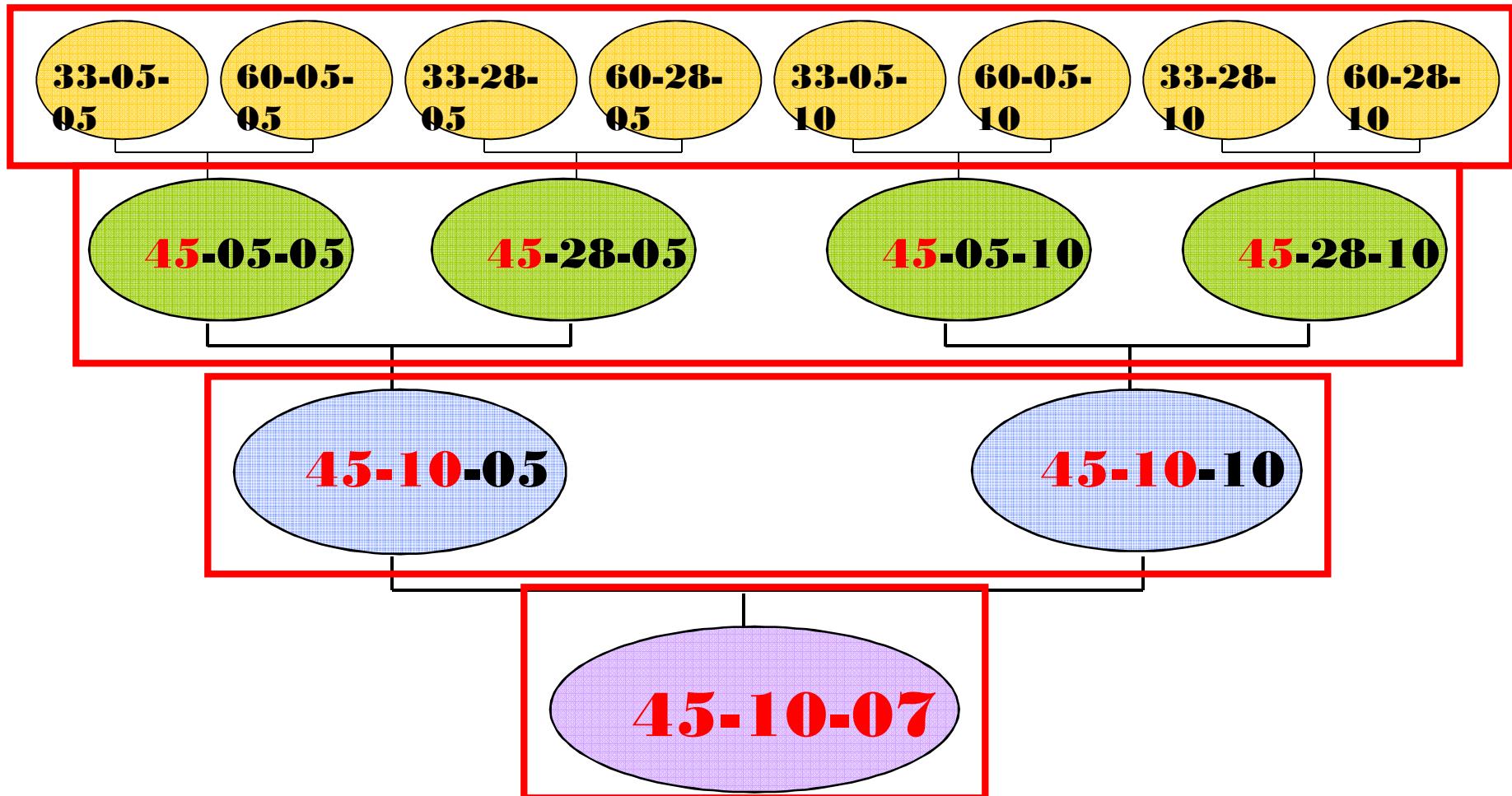
Initial IMF Fuel Cycle Interpolation Scheme

- Three independent variables
 - Burnup of UO_2 fuel
 - 33, 60, and 100 GWd/t
 - Cooling time after initial UO_2 cycle
 - 5, 28, and 50 years
 - Cooling time between IMF cycles
 - 5 and 10 years
- Five cycles for each data set
- Two test cases
 - 45 GWd/t burnup, 10 year initial cooling, 7 year IMF cooling
 - 75 GWd/t burnup, 45 year initial cooling, 7 year IMF cooling



Interpolation Scheme (Cont.)

Example: QUANTUM SARTORIUS W/ 1000 J/mol of fundamental cooling time. 715.70 m/s of cooling





Initial Homogeneous Assembly Results

- TRUO₂ Mass Fractions

45 GWd/t burnup, 10 year initial cooling, and 7 year IMF Cooling			
	Predicted	Actual	Error (%)
Cycle 0	24.21	23.75	1.95
Cycle 1	35.40	37.21	4.86
Cycle 2	44.01	46.70	5.75
Cycle 3	50.48	53.45	5.55
Cycle 4	55.46	58.50	5.19

75 GWd/t burnup, 45 year initial cooling, and 7 year IMF Cooling			
	Predicted	Actual	Error (%)
Cycle 0	59.61	59.61	0.01
Cycle 1	63.93	64.28	0.54
Cycle 2	68.72	69.13	0.60
Cycle 3	72.47	72.87	0.55
Cycle 4	75.35	75.78	0.56

- Errors higher with lower cooling time due to Pu-241 decay to Am-241
- 57.8% and 93.6% of 109 predicted values had errors less than 5% for 45 and 75 GWd/t burnup cases, respectively



Effects of Pu-241

- Pu-241 half-life: 14.4 years
- Decays to Am-241
- Fissile isotope to strong absorber
- Mass change varies greatly
 - 5 years: 78.61% remains
 - 28 years: 26.61% remains
 - 50 years: 9.01% remains
- **Cooling times of approximately 10.6 (60%) and 17.5 (43%) years should be added**



Revised IMF Fuel Cycle Interpolation Scheme

- Three independent variables
 - Burnup of UO_2 fuel
 - 33, 60, and 100 GWd/t
 - Cooling time after initial UO_2 cycle
 - 5, **10**, **17**, 28, and 50 years
 - Cooling time between IMF cycles
 - 5 and 10 years
- Five cycles for each data set
- Two test cases
 - 45 GWd/t burnup, **14** year initial cooling, 7 year IMF cooling
 - 75 GWd/t burnup, **40** year initial cooling, 7 year IMF cooling



Improved Results

- Case 45-14-07
 - Average error on TRUO_2 mass fraction: 1.3%
 - Overall
 - Values with less than 5% error: 102 of 109
 - Average error: 1.7%
 - Maximum error: 6.1%
- Case 75-40-07
 - Average error on TRUO_2 mass fraction: 1.1%
 - Overall
 - Values with less than 5% error: 104 of 109
 - Average error: 1.4%
 - Maximum error: 4.9%



Conclusions and Recommendations

- Mass flows of LWR-IMF fuel cycles were calculated using WIMS9
- Efficient interpolation schemes were proposed to predict system study variables
- Interpolations can now be used to accurately estimate various values within scenario analysis codes



Produced by University Communications

Questions?

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Abdellatif Yacout
Paul Wilson





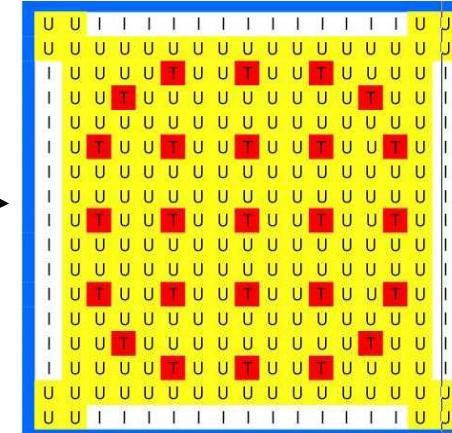
Backup slides



IMF Fuel Assemblies (Cont.)

- Heterogeneous Fuel Assemblies
 - IMF fuel pins are located at peripheral 52 positions of 17x17 typical PWR assembly
 - IMF fuel pins are made by blending TRUs of previous IMF cycle and LWR spent fuel
 - Cycle length is controlled by Uranium enrichment, blending ratio, and TRUO_2 mass fraction under power peaking of 1.2

TRU of previous
IMF cycle, TRU
of LWR spent
fuel, and ZrO_2



Heterogeneous IMF Assembly



LWR-UO₂ Cycle Interpolations

- Uranium Enrichment
 - 33 GWd/t (2.992% U-235), 60 (5.049%), 100 (8.500%)

	Actual Uranium Enrichment	Predicted Uranium Enrichment (linear)	Errors for Linear Interpolation (%)	Predicted Uranium Enrichment (quadratic)	Errors for Quadratic Interpolation (%)
45 GWd/t	3.872	3.918	1.18	3.879	0.18
75 GWd/t	6.294	6.394	1.56	6.287	0.12

- TRU vector after aging for varied cooling times
 - Three burnups (33, 60, and 100 GWd/t)
 - Five cooling times (5, 14, 28, 40, and 50 years)



LWR-UO₂ Cycle Interpolations (Cont.)

- Four test cases
 - 45 GWd/t burnup with 10 and 35 year cooling
 - 75 GWd/t burnup with 22 and 45 year cooling
 - Quadratic interpolation for burnup
 - Linear interpolation for cooling time
- Results

Error (%)	Number (out of 56)	Percentage
< 1	38	67.8
1 - 5	16	28.6
> 5	2	3.6

- Larger errors observed with smaller cooling times



Heterogeneous Results

- TRUO₂ Mass Fractions

45 GWd/t burnup, 10 year initial cooling, and 7 year IMF Cooling			
	Predicted	Actual	% Error
Cycle 0	20.49	21.47	4.58
Cycle 1	26.18	27.42	4.53
Cycle 2	29.93	31.50	4.99

75 GWd/t burnup, 45 year initial cooling, and 7 year IMF Cooling			
	Predicted	Actual	% Error
Cycle 0	36.97	37.05	0.22
Cycle 1	38.57	38.00	1.50
Cycle 2	40.76	40.67	0.22

- Uranium Enrichments

45 GWd/t burnup, 10 year initial cooling, and 7 year IMF Cooling			
	Predicted	Actual	% Error
Cycle 0	4.61	4.60	0.65
Cycle 1	4.75	4.75	0.14
Cycle 2	4.86	4.86	0.12

75 GWd/t burnup, 45 year initial cooling, and 7 year IMF Cooling			
	Predicted	Actual	% Error
Cycle 0	4.93	4.94	0.15
Cycle 1	5.03	5.02	0.28
Cycle 2	5.10	5.11	0.17

- 72.1% and 97.1% of 68 predicted values had errors less than 5% for 45 and 75 GWd/t burnup cases, respectively



Background

- AFCI (Advanced Fuel Cycle Initiative)
 - Reduce volume and toxicity of nuclear waste
 - Reduce proliferation threat posed by plutonium
 - Reclaim energy contained in spent fuel
- Transuranic Recycling in Commercial Light Water Reactors (LWRs)
 - Manages the inventory of transuranics (TRU) in commercial spent nuclear fuel (CSNF) and impedes further accumulation
 - Helps increase the loading capacity of high-level wastes in the Yucca Mountain repository
 - Capable of utilizing a large capacity of existing nuclear reactor facilities



Methodology - Codes

- WIMS9
 - 172 group neutron library based on JEF2.2
 - Heavy nuclides and about 100 fission products are explicitly traced in irradiation
 - Calculates physics parameters (eigenvalues and power peaking)
 - Creates one group cross sections for ORIGEN2.1 calculations
- ORIGEN2.1
 - Performs depletion calculation to generate spent fuel composition using one group cross sections generated by WIMS9
 - Simulates cooling, reprocessing, and aging processes



Trends Observed

- Values increase with burnup, cooling time, and cycle number
 - TRUO_2 mass fraction
 - Charge mass
 - Discharge mass
 - Uranium Enrichment
- Blending ratio decreases between cycle 1 and cycle 2 in high burnup and initial cooling time cases
- Exponential interpolation between cooling times can improve predictions for ^{241}Pu mass fraction
 - No closed form solution for increasing quantities