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

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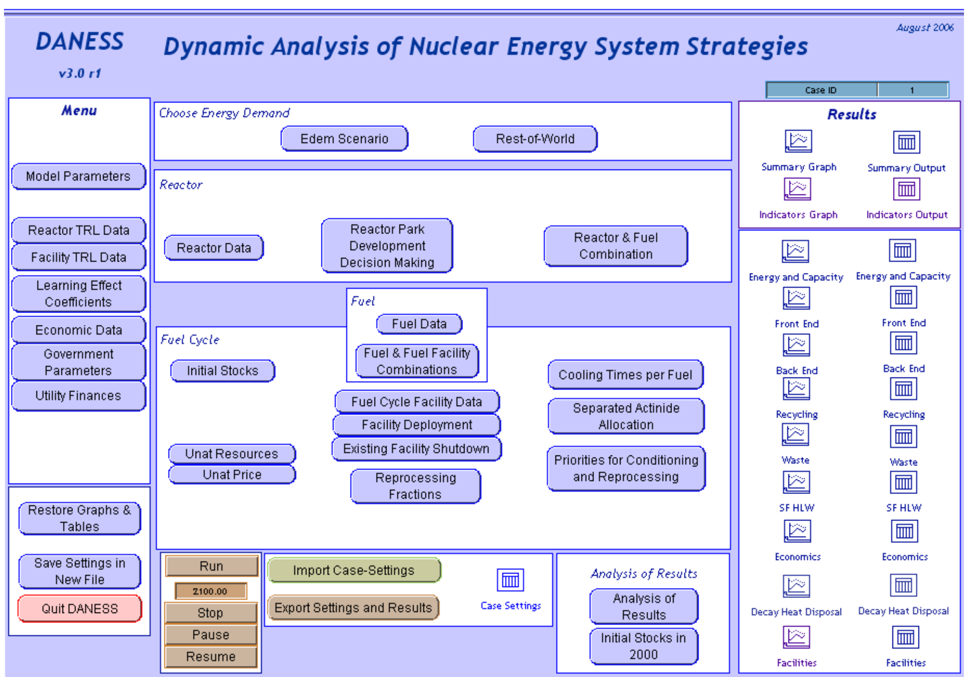
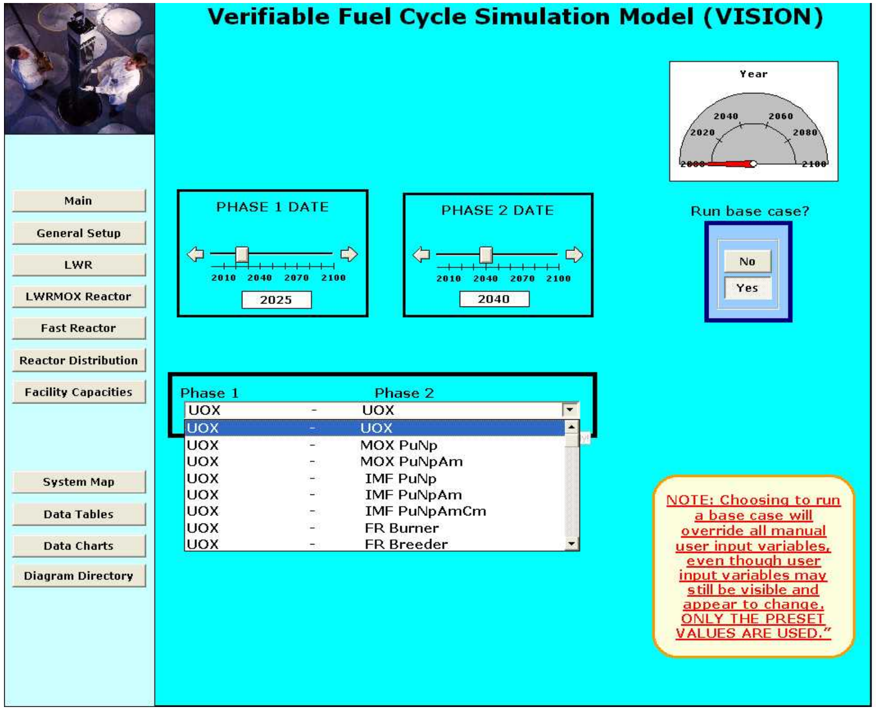
Outline

- 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

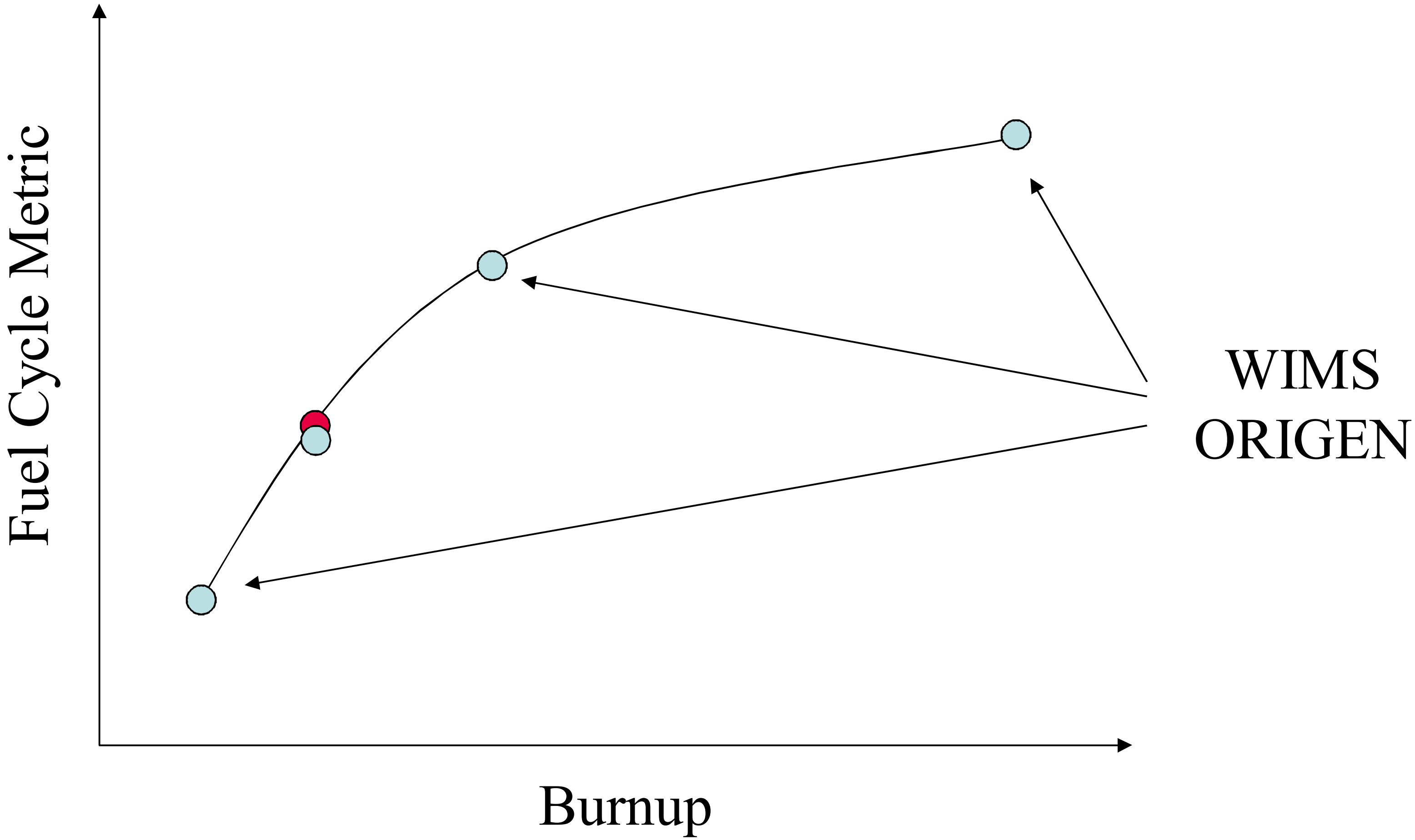




Scenario Analysis Codes (Cont.)

- Accurate mass flows require knowledge of
  - $TRUO_2$ 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

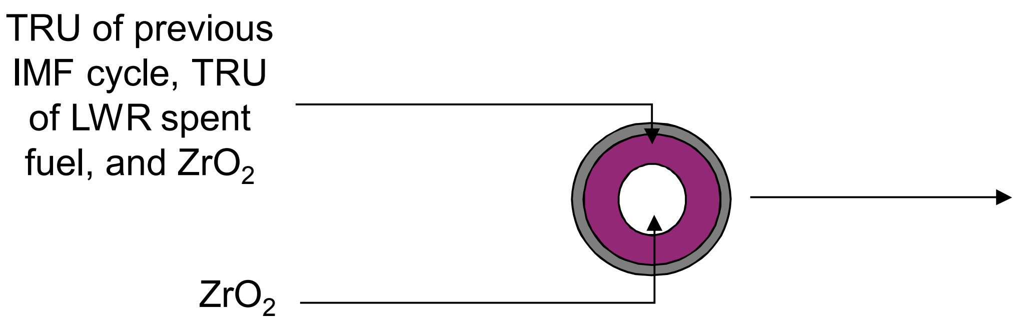
- Pu, Np, and Am extracted from spent nuclear fuel

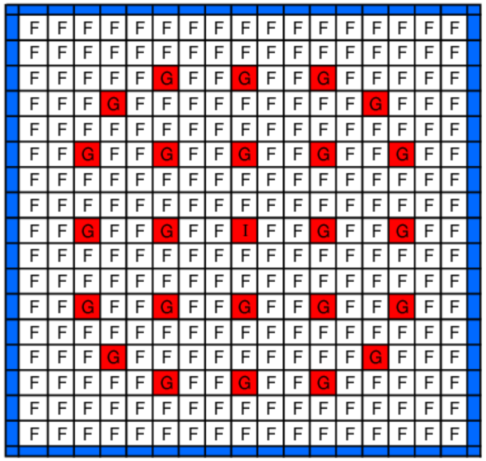
- Placed in an inert matrix material which is:
  - Neutron transparent
  - Chemically stable
  - Radiation damage resistant
  - Economically reasonable

- Zirconia stabilized by yttrium oxide and combined with spinel to compensate for zirconia matrix's low conductivity

IMF Fuel Assembly Geometry

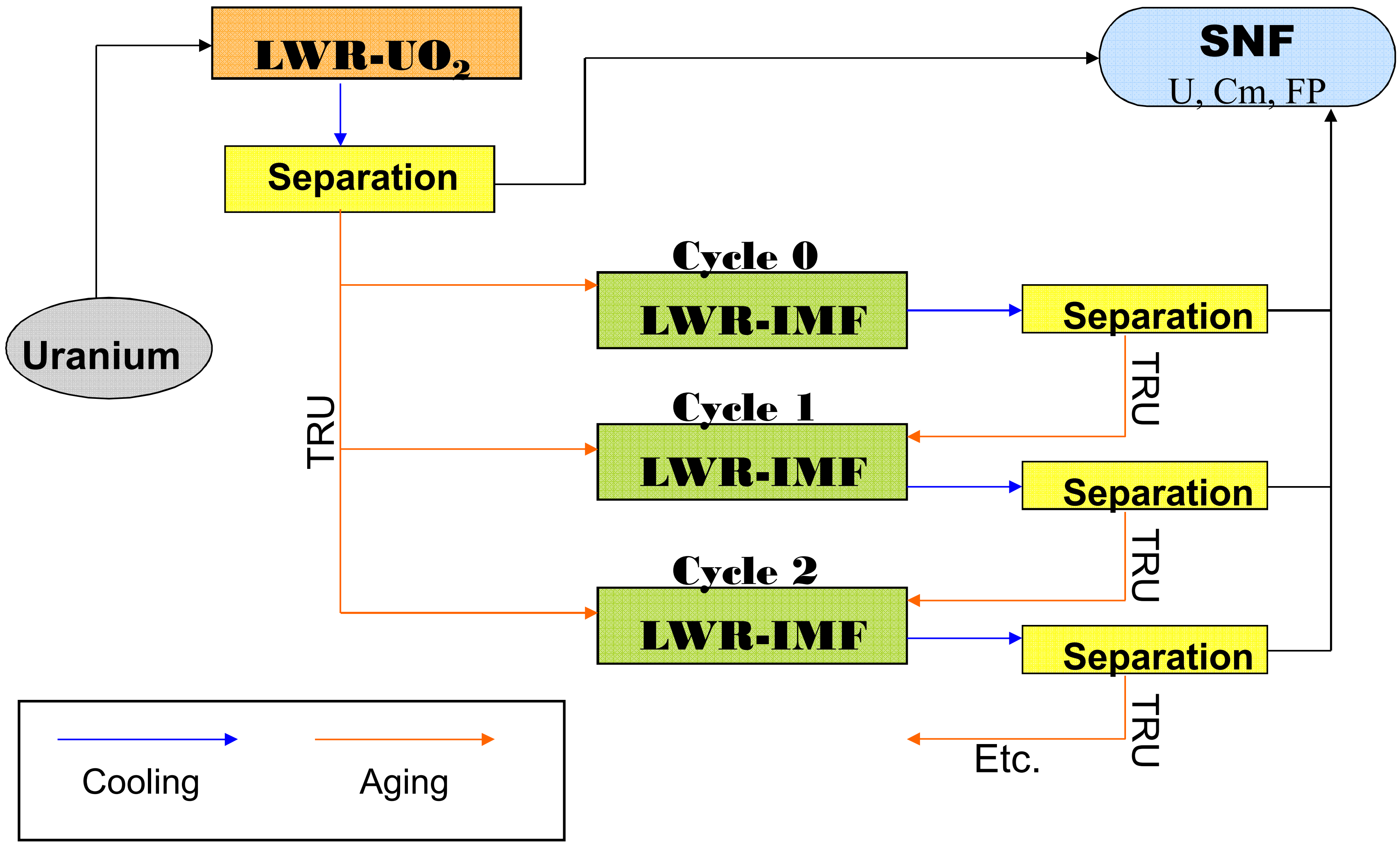
- Homogeneous Fuel Assemblies
  - IMF fuel pins are located at all fuel pins positions of 17x17 typical PWR assembly
  - IMF fuel pins are made by blending TRUs of previous IMF cycle and LWR spent fuel
  - Blending ratio and $TRUO_2$ mass fraction are key parameters to maintain a desired cycle length





Homogeneous IMF Assembly

IMF Cycle



LWR-UO2
SNF
U, Cm, FP
Separation
Uranium
TRU
Cycle 0
LWR-IMF
Separation
TRU
Cycle 1
LWR-IMF
Separation
TRU
Cycle 2
LWR-IMF
Separation
TRU
Etc.
Cooling
Aging

IMF Calculations

- $TRUO_2$ mass fraction
- Radius of zirconium center

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

- 95% theoretical density

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

- Charge mass

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

- Discharge mass
- Blending ratio
- Critical burnup

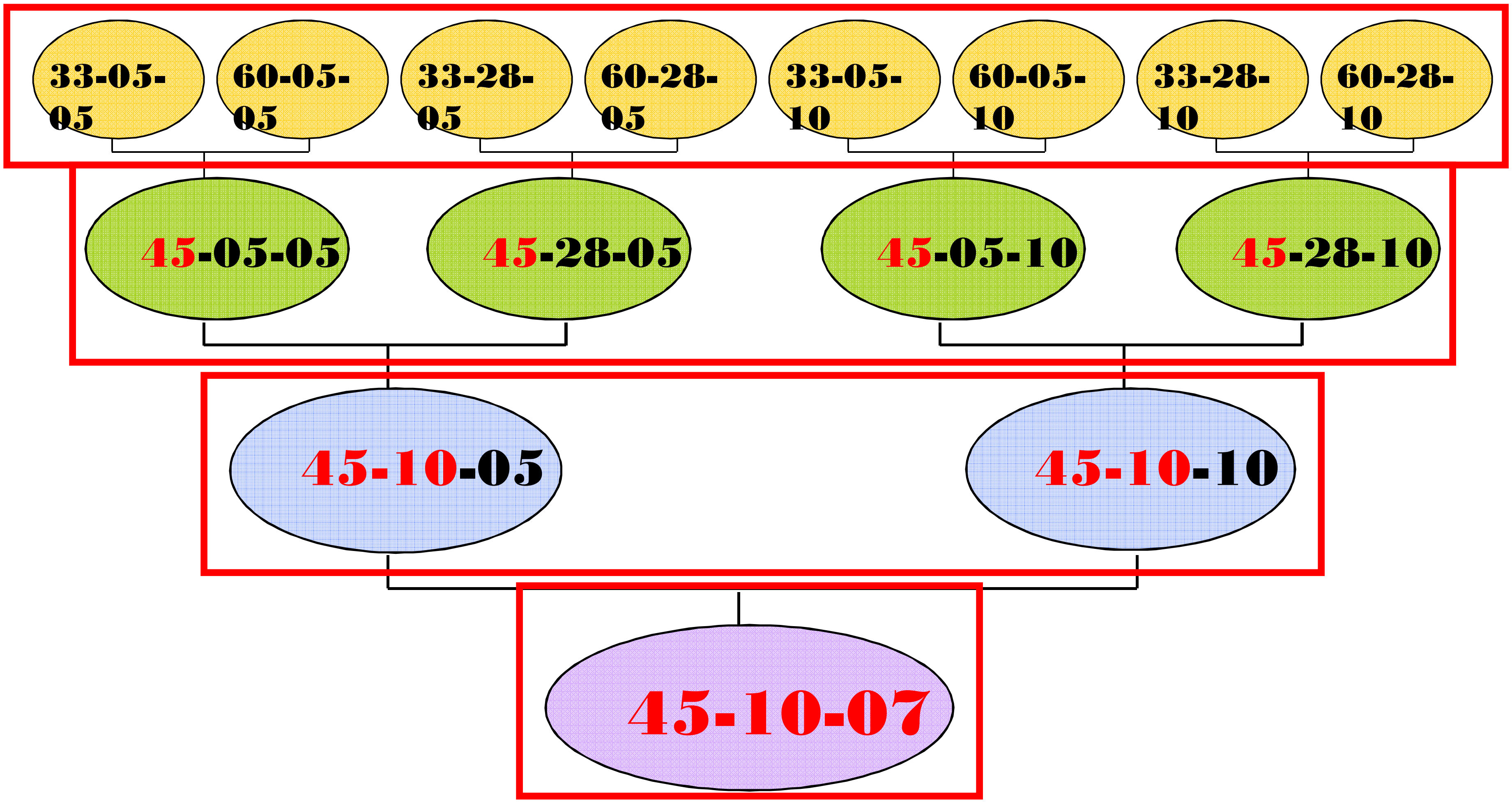
$$B_c = \frac{n+1}{2n} B_d$$

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: [illegible] cooling



Initial Homogeneous Assembly Results

- $TRUO_2$ 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

Questions?

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Paul Wilson

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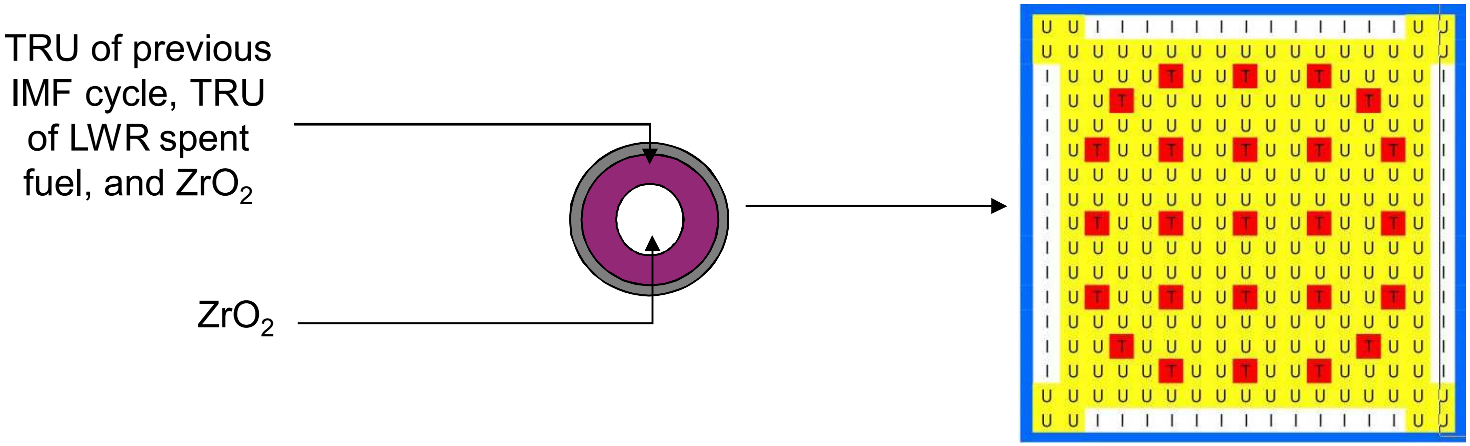
Backup slides

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



Heterogeneous IMF Assembly

LWR-UO_2 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-UO_2 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

- $TRUO_2$ 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