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Validation of Monte Carlo Neutron Physics Codes for Fully Ceramic Microencapsulated PWR Fuel Lattice

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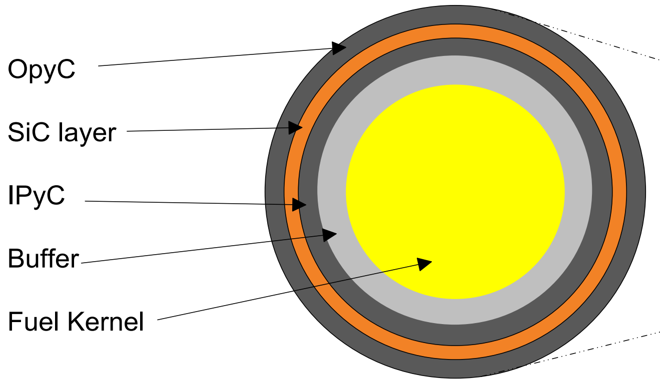
Outline

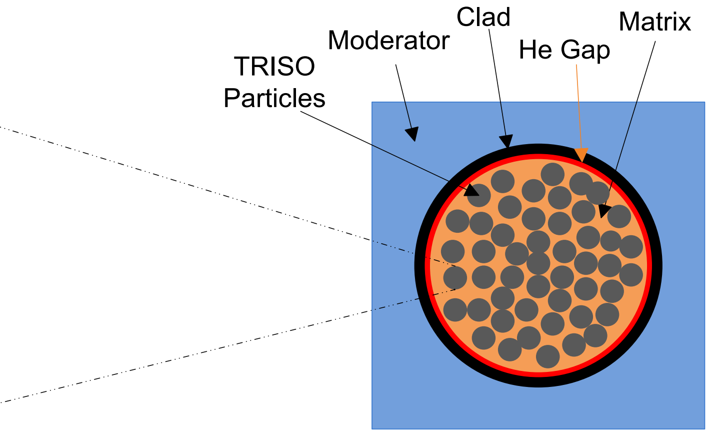
- A brief on TRISO particle & FCM fuel
- History of TRISO fuel
- Concept of PWR with FCM
- Treatment of double heterogeneity
- Monte Carlo Codes (MVP & Serpent)
- Pin Cell Validation
- Lattice Level Validation
- Summary/Conclusion

A brief on TRISO and FCM fuel

- TRISO Particles
  - Tiny spherical particle containing fuel (kernel).
  - Layers surrounding kernel (Buffer, IPyC, SiC, OPyC).
- FCM Fuel
  - TRISO Particles highly packed in SiC Matrix



TRISO Cross-section

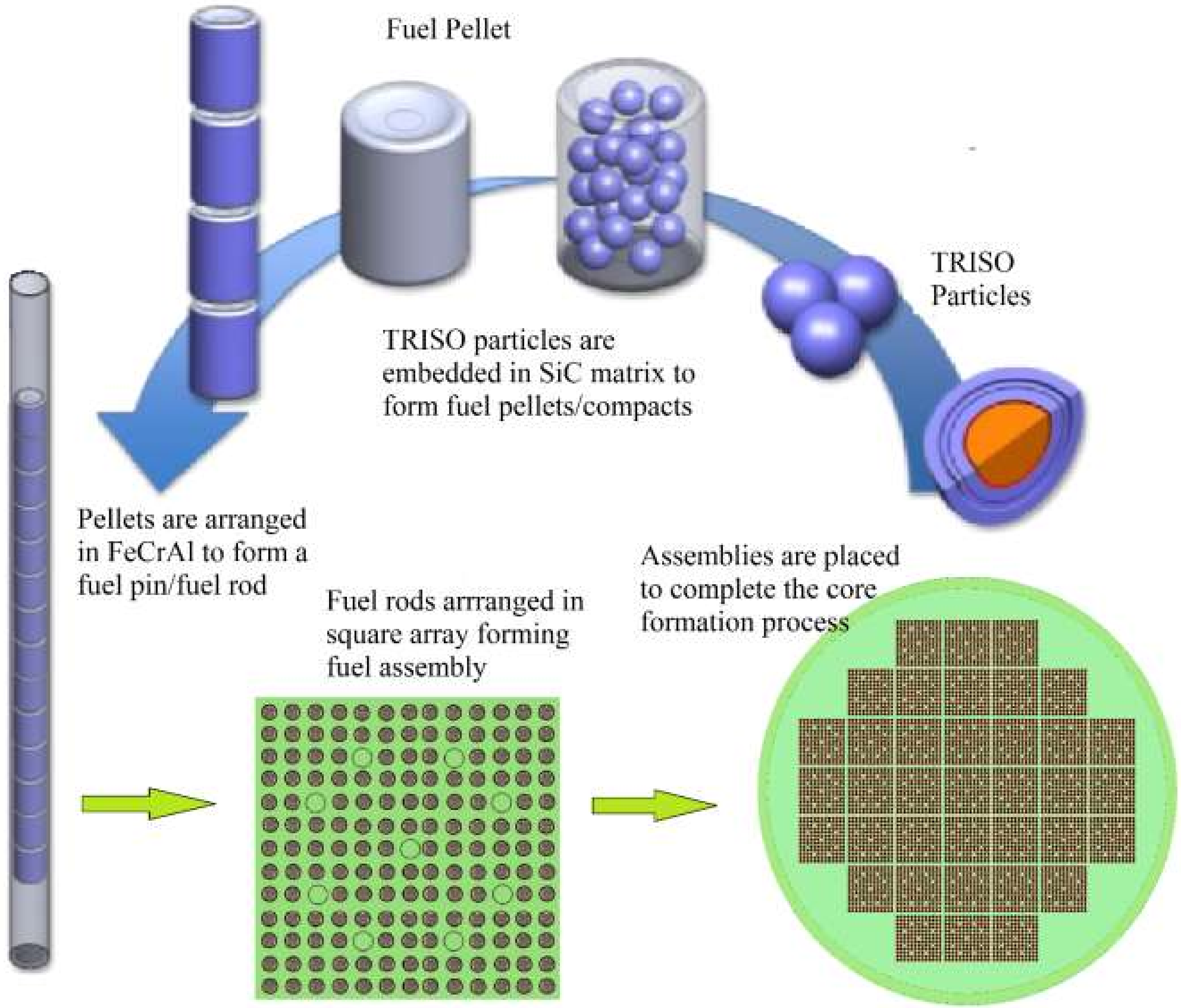


Single FCM Fuel Cell

History of TRISO fuel

- Invention and Initiation of TRISO Manufacturing
  - 1957: Invented by R. Huddle in Harwell, UK
  - 1964-75: DRAGON, UK .1st demonstration HTGR
  - 1966-1988: AVR Project, Jülich, Germany. Pebble-bed
  - 1967-1974: Peach Bottom-1, Pennsylvania, USA. HTGR
  - 1998 : HTTR project, Japan. HTGR
  - 2000: HTR-10, China. Pebble-bed
  - 2011: FCM Concept, FCRD Deep Burn Program, US-DOE

Concept of PWR with FCM Fuel



Treatment of Double Heterogeneity

Double Heterogeneous Fuel

Level-1: Multi Layered Nature of TRISO

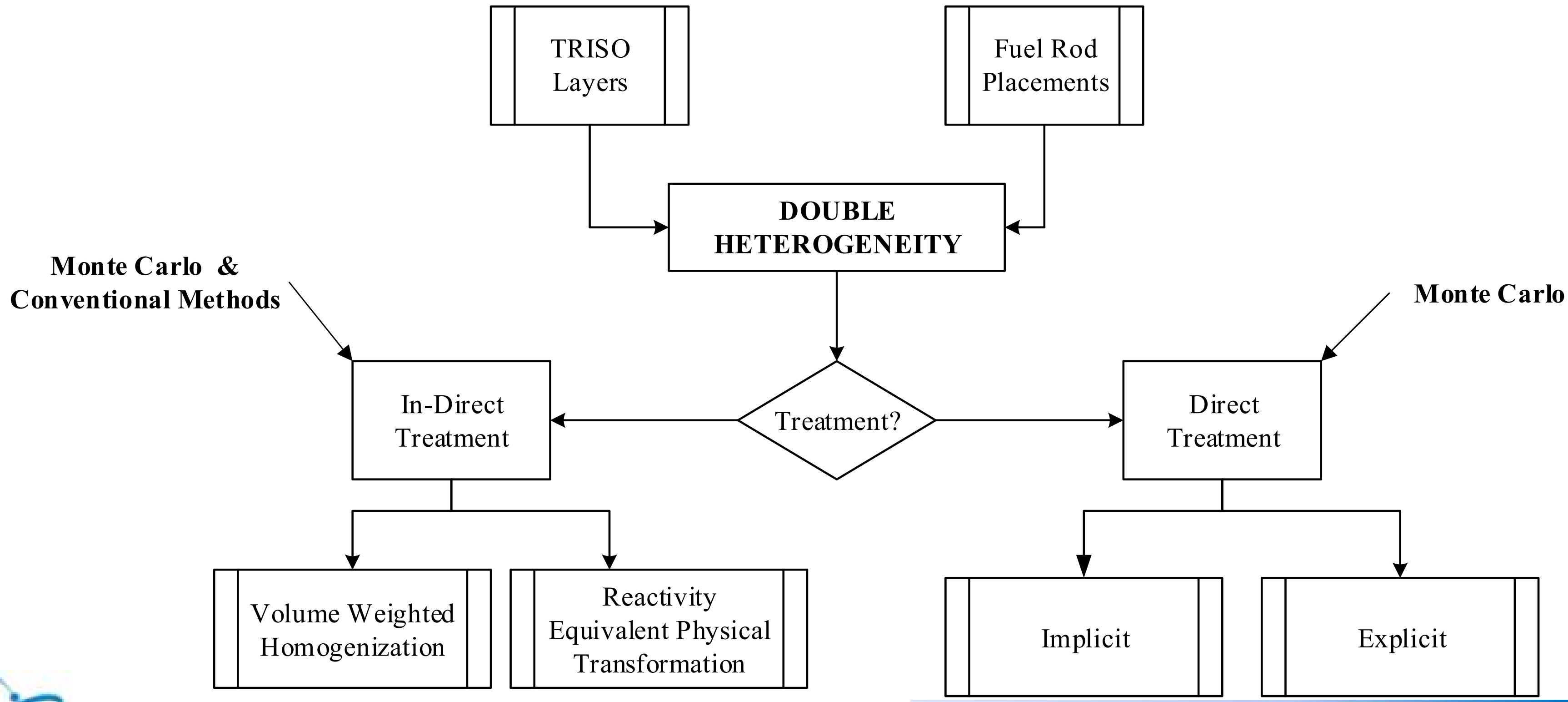
Level-2: Fuel Rod/Assembly Geometry

Direct Treatment

Implicit/Explicit Modeling in MC Code

In-Direct Treatment

Homogenization of Fuel Region



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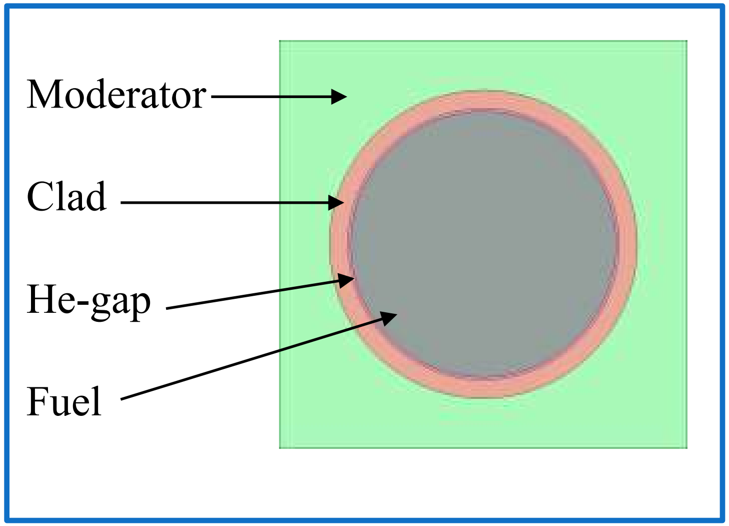
Monte Carlo Codes (MVP & Serpent)

- Monte Carlo codes
  - MVP by JAEA, Japan using JENDL-3.3
  - Serpent by VTT, Finland using ENDF/B-VII.0
    - *Capable of modeling doubly heterogeneous geometries like Pebble bed, HTGR or FCM in implicit and explicit manner.*
    - *Can perform burnup calculations for DH geometries.*
- High computational resources to reduce the statistical fluctuations to less than 4 pcm for eigenvalues.
  - For solid fuel case, 100,000 particles 1100 batches
  - FCM Case, 100,000 particles in 5500 batches

Pin Cell Validation

- VERA benchmark revision 4. with KENO-IV using ENDF/B-VI.1
  - Pin cell validation
    - K-infinity estimation against various conditions.
    - *Transformation of solid UO_2 pin cell into FCM pin cell.*
    - FCM pin cell validation



Problem #	Temperature (°K)		Moderator Density
	Moderator	Fuel	(g/cm³)
1A	565	565	0.743
1B	600	600	0.661
1C	600	900	0.661
1D	600	1200	0.661

Description	Value/Unit
Fuel Radius	0.4095 cm
He-gap thickness	0.0085 cm
Clad thickness	0.047 cm
Pin pitch	1.26 cm
UO_2 Enrichment	3.11 w/o
Boron	1300 ppm

Pin Cell Validation contd.

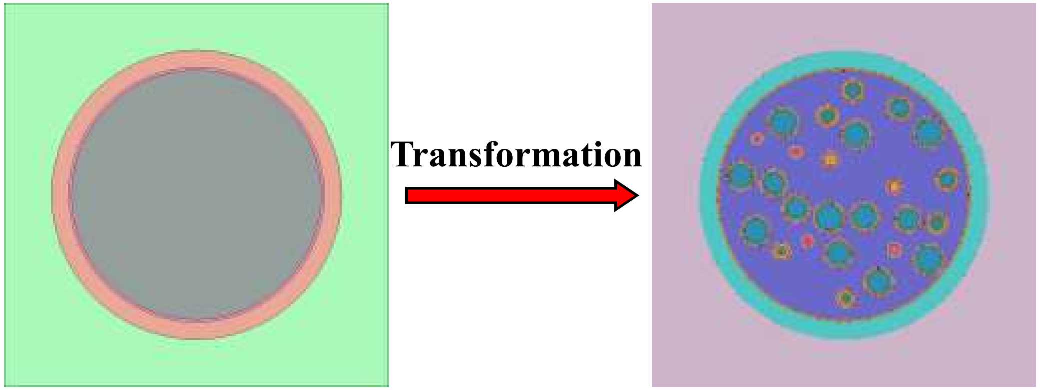
Case #	Reference	Unc. (±)	Serpent	Unc. (±)	R/Err	MVP	Unc. (±)	R/Err
1A	1.187038	0.000054	1.18572	0.000046	-0.11%	1.18372	0.000041	-0.28%
1B	1.182149	0.000068	1.18131	0.000048	-0.07%	1.18037	0.000046	-0.15%
1C	1.171720	0.000072	1.17121	0.000049	-0.04%	1.16984	0.000045	-0.16%
1D	1.162603	0.000071	1.16266	0.000050	0.00%	1.16098	0.000046	-0.14%

- Max relative error of Serpent is 0.11 %
- Max Relative error for MVP 0.28 %.
- Excellent agreement

Pin cell Validation contd.

- Transformation of standard fuel pin into FCM fuel pin
- Zircaloy, FeCrAl Clad
- PF=0.50
- Transformation:
- *Fuel: UO_2 Solid → UC FCM*

  Enr. : 3.11 w/o → 12.65 w/o



Case#	Serpent	Unc. (±)	MVP	Unc. (±)	R/Err
1A	1.398810	0.000037	1.405150	0.000035	0.45%
1B	1.411880	0.000037	1.415570	0.000035	0.26%
1C	1.401970	0.000038	1.405090	0.000037	0.22%
1D	1.393530	0.000039	1.395840	0.000038	0.17%

Pin cell Validation contd.

- FeCrAl Clad case

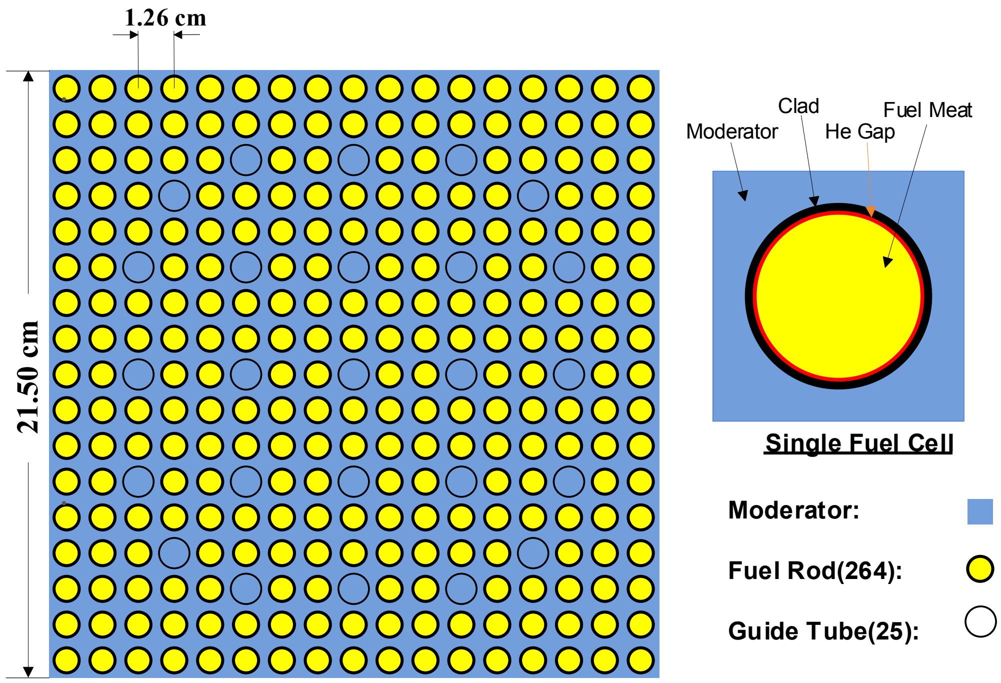
Problem #	Serpent	Unc. (±)	MVP	Unc. (±)	Rel Diff
1A	1.387350	0.000038	1.394180	0.000036	0.49%
1B	1.400630	0.000038	1.405520	0.000037	0.35%
1C	1.391020	0.000039	1.395360	0.000037	0.31%
1D	1.382550	0.000039	1.386530	0.000038	0.29%

- Max relative difference of MVP is
  - ✓ 0.45% for Zircaloy Clad Case
  - ✓ 0.49% for FeCrAl Clad Case
- Excellent agreement found in both cases

Lattice Level Validation

– Lattice level validation, Problem#2C

- K-inf values against HFP
- Pin power distribution (1/8 FA)
- *Transformation of solid UO_2 lattice into FCM lattice.*
- Validation of FCM results



- Fuel Assembly Pitch = 21.5 cm
- Inter Assembly half gap = 0.04 cm
- Guide Tube inner radius = 0.561 cm
- Guide Tube thickness = 0.41 cm

- Hot Full Power (HFP) Condition
  - Moderator Temp = 600 ^oK
  - Fuel Temperature = 900 ^oK
  - Moderator Density = 0.661 g/cm^3

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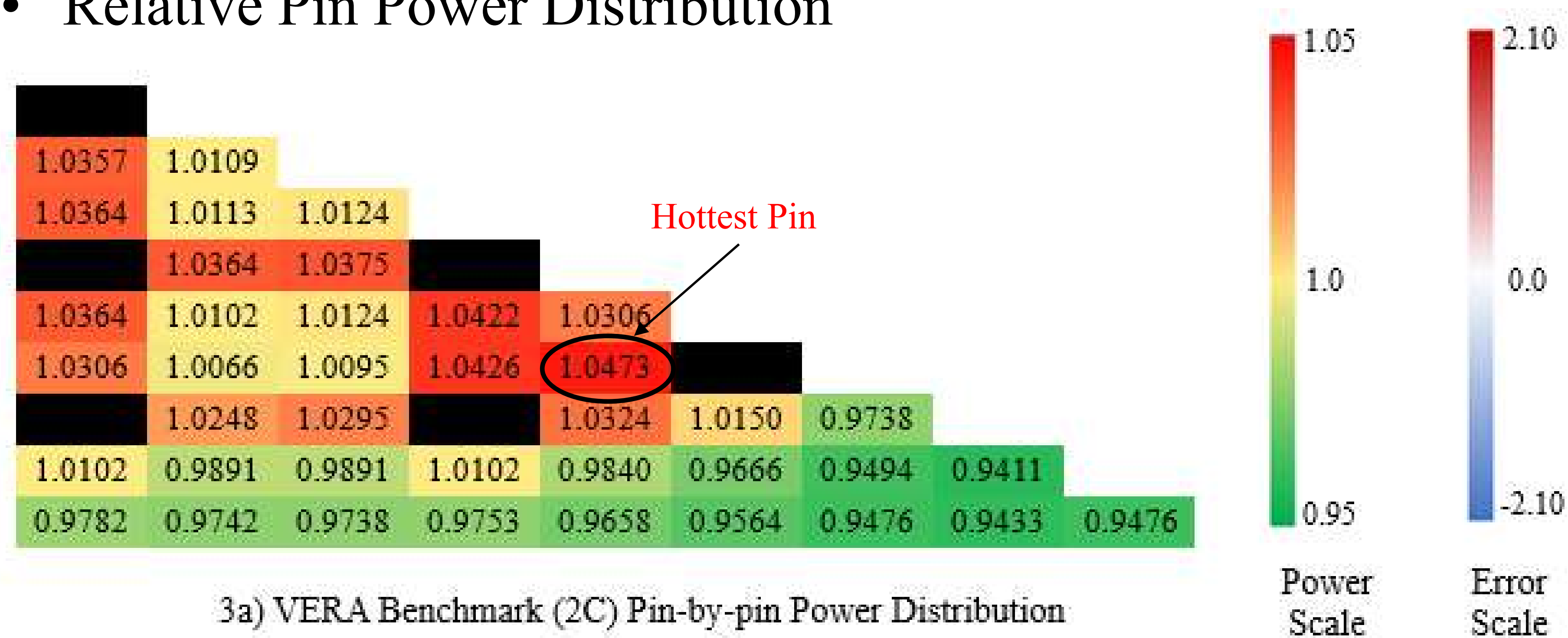
Lattice Level Validation contd.

- K-infinity

Case#	Reference	Unc. (±)	Serpent	Unc. (±)	R/Err	MVP	Unc. (±)	R/Err
2C	1.173751	0.000023	1.17339	0.000021	-0.03%	1.17169	0.000019	-0.18%

- Relative Pin Power Distribution



3a) VERA Benchmark (2C) Pin-by-pin Power Distribution

Lattice Level Validation contd.

- Relative Pin Power Distribution *contd.*

Hottest Pin

1.0379	1.0139							
1.0386	1.0139	1.0142						
	1.0384	1.0398						
1.0365	1.0119	1.0145	1.0447	1.0325				
1.0327	1.0087	1.0114	1.0439	1.0489				
	1.0258	1.0268		1.0333	1.0154	0.9739		
1.0105	0.9894	0.9891	1.0097	0.9837	0.9654	0.9486	0.9381	
0.9760	0.9721	0.9712	0.9729	0.9638	0.9537	0.9439	0.9381	0.9407

3b) Pin-by-pin Power Distribution by SERPENT

0.21	0.30							
0.22	0.26	0.17						
	0.19	0.22						
0.01	0.17	0.20	0.24	0.18				
0.21	0.21	0.19	0.12	0.15				
	0.10	-0.27		0.09	0.04	0.01		
0.03	0.03	0.00	-0.05	-0.03	-0.12	-0.09	-0.31	
-0.22	-0.22	-0.27	-0.25	-0.21	-0.29	-0.39	-0.55	-0.73

3c) SERPENT Relative Error (%)

Hottest Pin

1.0386	1.0137							
1.0388	1.0162	1.0146						
	1.0414	1.0429						
1.0368	1.0150	1.0169	1.0477	1.0330				
1.0327	1.0106	1.0135	1.0465	1.0518				
	1.0277	1.0294		1.0359	1.0164	0.9709		
1.0089	0.9895	0.9895	1.0108	0.9833	0.9645	0.9468	0.9326	
0.9700	0.9687	0.9682	0.9699	0.9598	0.9492	0.9382	0.9314	0.9277

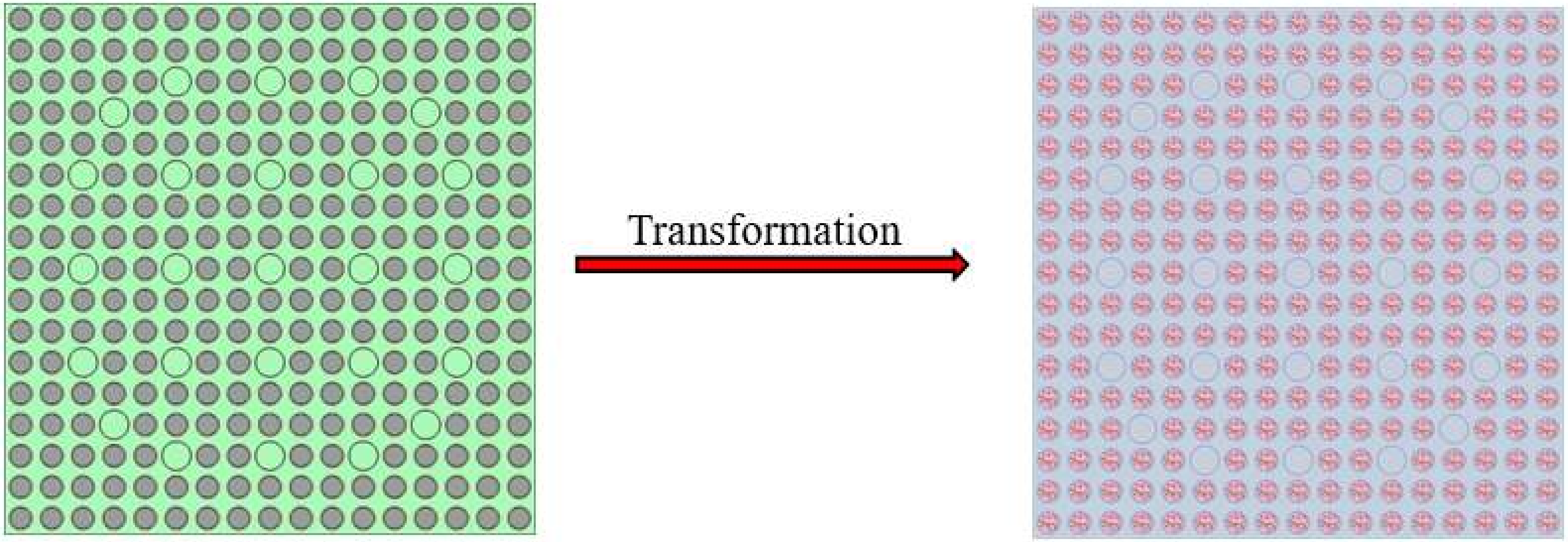
3d) Pin-by-pin Power Distribution by MVP

0.28	0.28							
0.23	0.49	0.22						
	0.48	0.52						
0.04	0.47	0.45	0.53	0.23				
0.21	0.40	0.40	0.38	0.43				
	0.29	-0.01		0.34	0.14	-0.30		
-0.13	0.04	0.04	0.06	-0.07	-0.22	-0.28	-0.90	
-0.83	-0.57	-0.58	-0.56	-0.62	-0.75	-1.00	-1.26	-2.10

3e) MVP Relative Error (%)

Lattice Level Validation contd.

- FCM Assembly



- Conservation of initial fissile content
- Packing fraction = 0.50
- UO_2 ⟶ UC ; Enrichment: 3.11 w/o ⟶ 12.65 w/o
- All other dimension, material specs and conditions are same

Lattice Level Validation contd.

- K-infinity and Relative Pin Power Distribution

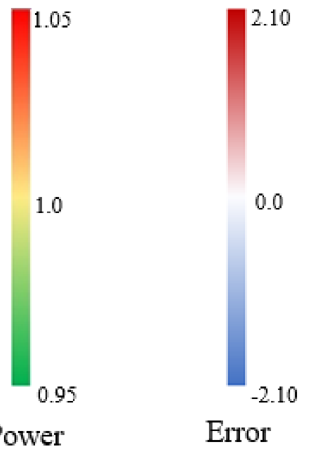
Table 2-6. FCM Pin Cell K-infinity Values & Relative Difference of MVP

Clad	SERPENT	Uncertainty (±)	MVP	Uncertainty (±)	Rel Diff
Zircaloy	1.381930	0.000015	1.388130	0.000016	0.45%
FeCrAl	1.367080	0.000017	1.374750	0.000017	0.56%

1.0355	1.0123							
1.0359	1.0133	1.0131						
	1.0357	1.0371						
1.0337	1.0113	1.0134	1.0413	1.0298				
1.0306	1.0077	1.0102	1.0409	1.0446				
	1.0241	1.0249		1.0306	1.0142	0.9753		
1.0096	0.9903	0.9895	1.0090	0.9846	0.9681	0.9521	0.9429	
0.9781	0.9743	0.9737	0.9751	0.9661	0.9571	0.9478	0.9431	0.9447

Hottest Pin

5a) Relative Pin-by-pin Power Distribution by Serpent



1.0370	1.0123							
1.0371	1.0146	1.0126						
	1.0394	1.0410						
1.0347	1.0129	1.0154	1.0456	1.0305				
1.0311	1.0096	1.0123	1.0447	1.0496				
	1.0267	1.0277		1.0341	1.0164	0.9734		
1.0088	0.9899	0.9895	1.0100	0.9839	0.9665	0.9498	0.9368	
0.9718	0.9700	0.9696	0.9713	0.9622	0.9521	0.9417	0.9352	0.9321

Hottest Pin

5b) Relative Pin-by-pin Power Distribution by MVP

0.15	0.01							
0.12	0.13	-0.05						
	0.37	0.38						
0.10	0.16	0.20	0.42	0.07				
0.05	0.18	0.21	0.37	0.47				
	0.26	0.28		0.35	0.22	-0.20		
-0.08	-0.04	0.00	0.09	-0.07	-0.17	-0.24	-0.65	
-0.65	-0.44	-0.42	-0.40	-0.41	-0.52	-0.64	-0.83	-1.34

5c) MVP Relative Difference/ %

Summary and Conclusion

- Excellent agreement of K-infinity values for pin cell and lattice cases for both reference and FCM.
- Relative pin power distribution for both cases is in very good agreement
- Both codes predicted the exact location for hottest pin

➢ ***Thus use of Serpent and MVP for neutronic studies of FCM loaded PWR will provide reliable results***

THANK YOU