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VARIANCE REDUCTION IN HIGH RESOLUTION COUPLED MONTE CARLO - THERMA-HYDRAULICS CALCULATIONS

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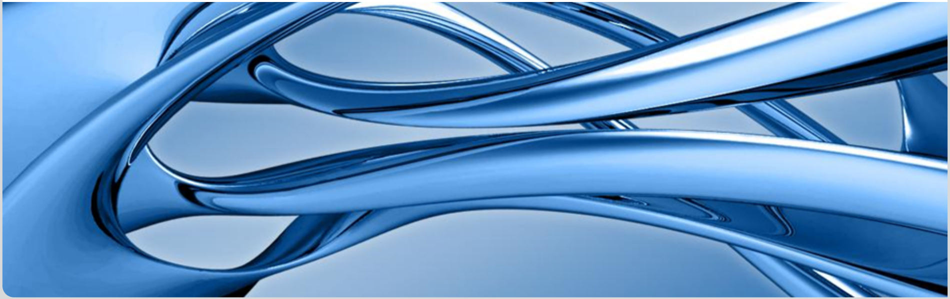

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Variance reduction

- Large power gradient between the core center and the periphery.
- Large statistical uncertainties in the low power regions.
- Detailed pin-level spacial estimate of the power profile must be supplied to the TH code.
- The MC statistical uncertainties are propagated to the TH solution.
- Might lead to convergence failure of the TH solution and of the entire coupled system.
- Adequate variance reduction techniques needed.

Convergence of the coupled calculation and stochastic noise (1/2)

- The coupled calculation **MCNP** - **SUBCHANFLOW** is repeated until convergence.

$$\epsilon = \max_{\text{pin,z}} \left| \frac{T^{n+1}_{\text{fuel},P(\text{pin,z})} - T^{n}_{\text{fuel},P(\text{pin,z})}}{T^{n+1}_{\text{fuel},P(\text{pin,z})}} \right| .$$

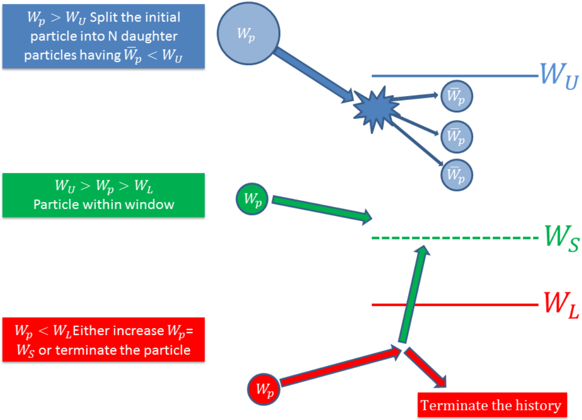
- Since the Fission heat deposition $P(\text{pin}, \text{z})$ of a certain pin in a volume V around a particular $\boldsymbol{z} \in \mathbb{R}$ is tallied by a Monte Carlo code, the associated variance is propagated to the hydraulic distributions.
- The new convergence parameter becomes

$$\epsilon = \max_{\text{pin,z}} \left| \frac{T^{n+1}_{\text{fuel},P(\text{pin,z})} - T^{n}_{\text{fuel},P(\text{pin,z})} + \delta_{T^{n+1}_{\text{fuel},P(\text{pin,z})}} - \delta_{T^{n}_{\text{fuel},P(\text{pin,z})}}}{T^{n+1}_{\text{fuel},P(\text{pin,z})} + \delta_{T^{n+1}_{\text{fuel},P(\text{pin,z})}}} \right| .$$

Convergence of the coupled calculation and stochastic noise (2/2)

- The convergence parameter ϵ is affected by the induced variance $\delta_{T_{\text{fuel},P(\text{pin,z})}}$.
- To stabilize the coupled calculation itself, the coupled scheme between **MCNP** and **SUBCHANFLOW** uses relaxation technique based on stochastic approximation.
- To reach the desired convergence without running extensive number of coupled iterations, one has to reduce the variance of the fission heat deposition.

The GVR scheme (1/2)



$W_p > W_U$ Split the initial particle into N daughter particles having $\overline{W}_p < W_U$

$W_U > W_p > W_L$
Particle within window

$W_p < W_L$ Either increase W_p= W_S or terminate the particle

Terminate the history

Figure : Weight Windows in **MCNP** .

The GVR scheme (2/2)

- In MCNP both W_S and W_U are integer multiples C_S and C_U of the lower bound W_L. The basic idea of GVR is to obtain uniform non-analog particle density. The analog particle density in a particular volume V is given by

$$n_k = \frac{\phi_k}{V} \approx m_k \overline{w}_k.$$

- $m_k \overline{w}_k$ is the product of the non-analog particle density times the average weight. If we set

$$\overline{w}_k \propto \phi_k,$$

then the non-analog particle density will be approximately constant. The lower bound of the weight window in this case is

$$W_{low} = \left(\frac{\beta + 1}{2}\right) \frac{\phi_k}{\underset{k}{Max}\, \phi_k}.$$

The uniform fission site method

- **In essence, the surplus of neutrons in the high power regions is used to improve the statistics of the low power regions.**
- The number of neutrons per fission is modified to

$$N_f^{mod} = \lambda(\mathbf{r}) \times w \frac{\nu\Sigma_f}{\Sigma_t k_{eff}},$$
$$\lambda\left(\mathbf{r}\right)^{-1} = \frac{s_k}{< s_k >}.$$

- s_k is the fraction of the fission source in a mesh element k. To accumulate s_k special source mesh was implemented.
- To keep the Monte Carlo transport unbiased the starting weight of the particles has to be reduced by $\lambda\left(\mathbf{r}\right)$.

Demonstration of the MCNP - SUBCHANFLOW coupling scheme

- Demonstrated on the international NEA PWR UOX-MOX benchmark.
- Pin-by-pin resolution Monte Carlo simulation of real core loading with local thermal hydraulic feedback.
- Local temperature and density computed by the in-house code **SUBCHANFLOW**.
- In each Monte Carlo run 1×10^9 particles were simulated on 240 processor cores.

The uniform fission site method

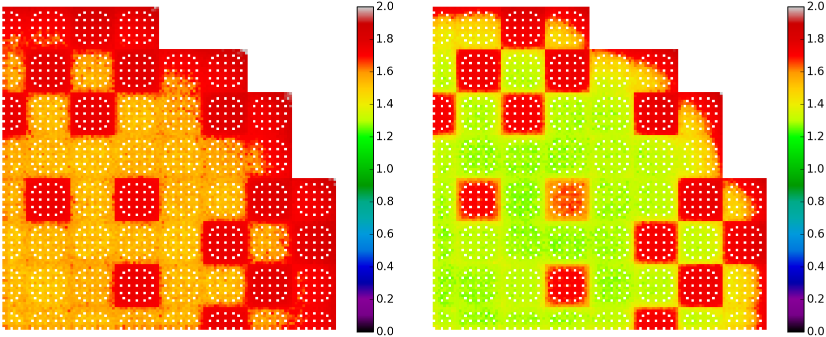
Numerical test

Table : Performance summary of the variance reduction techniques. 750 active cycles with 1×10^6 histories per cycle on quarter core model.

Calculation	Eigenvalue k_{eff}	FOM	run time (min)
Reference	1.15100 (2)	29.09	204
GVR	1.15096 (3)	33.15	596
UFS	1.15100 (3)	36.80	211

The uniform fission site method

Pin power relative error distribution for the first axial level



Reference simulation

UFS simulation

Figure : Relative error distribution in % for the bottom core slice (left) and the core mid-plane (right). Quarter assembly size mesh elements used for the UFS mesh.

Demonstration of the MCNP - SUBCHANFLOW coupling scheme (2/3)

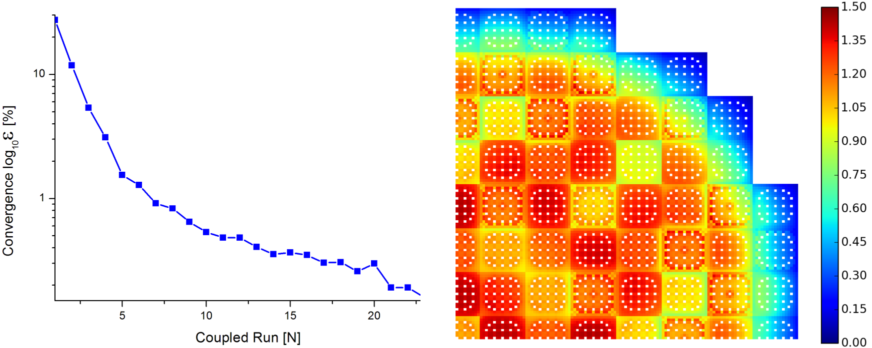


Figure : Convergence ϵ as a function of the coupled iteration [N] and two dimensional pin power distribution.

Demonstration of the MCNP - SUBCHANFLOW coupling scheme (3/3)

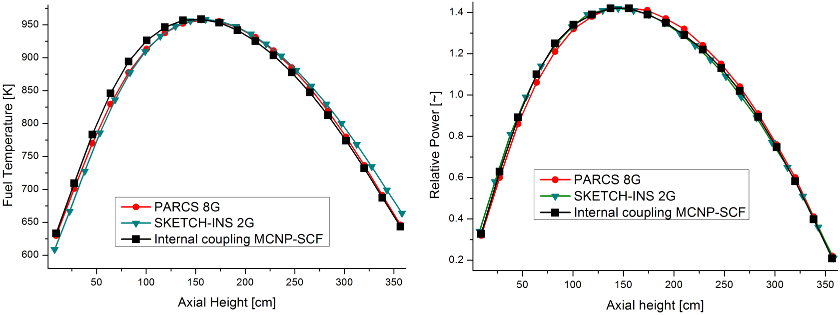


Figure : Core averaged fuel Doppler temperature and power distributions plotted as functions of the core height.

Comparison with the benchmark data

Table : Assembly power relative difference between ***SKETCH*** − ***INS2G*** and ***MCNP*** given in %.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
A	-3.59	-3.92	-2.95	-1.48	-0.13	1.94	3.61	3.45
B	-3.91	-3.36	-2.27	-1.32	-0.73	1.19	2.58	3.81
C	-2.93	-2.26	-2.14	-1.08	-0.42	0.47	3.45	3.73
D	-1.51	-1.37	-1.09	0.14	-0.74	0.27	1.24	2.41
E	-0.27	-0.86	-0.51	-0.79	-0.31	1.01	1.49	
F	1.71	1.06	0.39	0.22	0.98	-1.51	-0.01	
G	3.53	2.49	3.40	1.19	1.49	0.05		
H	3.39	3.79	3.65	2.36				

Comparisson with the benchmark data

Table : Assembly power relative difference between ***PARCS2G*** and ***MCNP*** given in %.

	1	2	3	4	5	6	7	8
A	-1.99	-2.27	-1.37	-0.66	0.34	0.61	1.37	2.01
B	-2.26	-2.01	-0.90	-0.15	0.01	1.09	0.50	1.97
C	-1.35	-0.89	-0.74	-0.18	0.06	0.52	1.55	2.71
D	-0.69	-0.20	-0.19	0.71	-0.04	0.19	-0.13	1.35
E	0.20	-0.12	-0.02	-0.08	0.29	-0.12	0.00	
F	0.37	0.96	0.44	0.14	-0.15	-1.13	0.13	
G	1.29	0.41	1.48	-0.18	-0.01	0.19		
H	1.95	1.95	2.63	1.30				

Comparisson with the benchmark data

Table : Assembly power relative difference between ***PARCS8G*** and ***MCNP*** given in %.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
A	-0.65	-1.32	-0.52	-0.18	0.83	-0.17	0.80	1.55
B	-1.31	-1.05	-0.08	-0.18	0.27	1.19	-0.99	1.38
C	-0.50	-0.07	-0.04	0.26	0.43	-0.25	0.98	1.72
D	-0.21	-0.23	0.24	0.93	0.18	0.16	-1.59	1.24
E	0.69	0.14	0.35	0.14	0.70	-0.32	-0.06	
F	-0.41	1.06	-0.32	0.11	-0.35	-2.52	0.20	
G	0.72	-1.08	0.93	-1.64	-0.06	0.26		
H	1.49	1.36	1.64	1.19				

Conclusions

- Optimized methods for reducing the variance were implemented.
- Combining the internal coupling **MCNP** - **SUBCHANFLOW** and the newly implemented UFS method allowed running large scale problem with TH feedback.
- Successful Monte Carlo simulation of a realistic core problem on pin-by-pin scale taking into account the local feedback effects.
- Converged solution of the criticality calculation was obtained within 35 hours.

QUESTIONS ?