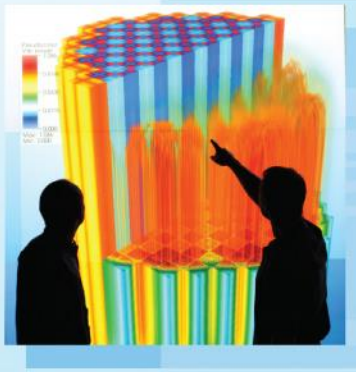
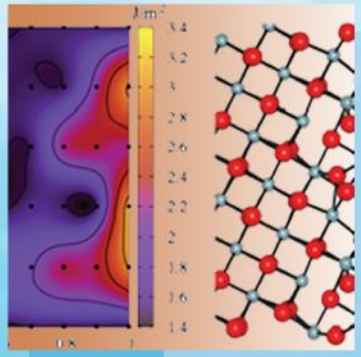
CASL-U-2014-0183-000

Power uprates
and plant life extension



Engineering design
and analysis

Science-enabling
high performance
computing



Fundamental science

Plant operational data

Consortium for Advanced Simulation of LWRs

NENE 2014 Conference Presentation: Simulation of the NPP KRSKO Startup Core with CASL Core Simulator, VERA-CS

Fausto Franceschini
Westinghouse Electric Company LLC

Marjan Kromar and Dušan Ćalić
Jožef Stefan Institute

Andrew T. Godfrey, Benjamin S. Collins, Thomas M. Evans, Jess C. Gehin
Oak Ridge National Laboratory

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

CASL-U-2014-0183-000

© 2014 Westinghouse Electric Company LLC. All Rights Reserved.

SIMULATION OF THE NPP KRSKO STARTUP CORE WITH THE CASL CORE SIMULATOR VERA-CS

F. Franceschini[1], M. Kromar[2], D. Ćalić[2], A. Godfrey[3], B. Collins[3], T. Evans[3], J. Gehin[3]

[1] Westinghouse Electric Company LLC

[2] Jožef Stefan Institute

[3] Oak Ridge National Laboratory

NENE 2014, September 8-11 2014, Portorož, Slovenia

Westinghouse

Jožef Stefan Institute

CASL

© 2014 Westinghouse Electric Company LLC. All Rights Reserved.

Outline

- Background: CASL and VERA-CS
- Topics: Krsko Startup Core
- Results:
  - Numerical Benchmarks
  - Startup Tests
- Conclusions

© 2014 Westinghouse Electric Company LLC. All Rights Reserved.

Consortium for Advanced Simulation of LWRs (CASL)

- DOE-funded Nuclear Energy Hub established in July 2010 for providing advanced modelling and simulation solutions for commercial nuclear reactors.
- Consortium of ten core partners with numerous contributing members, led by Oak Ridge National Laboratory (ORNL) and with Westinghouse as the Industry fuel vendor representative.

- The main technology that drives CASL's modelling and simulations is the Virtual Environment for Reactor Applications (VERA)

- VERA aims at enhancing the simulation capabilities for nuclear reactors by developing an integrated suite of computational tools with higher-fidelity physics than the current tools

© 2014 Westinghouse Electric Company LLC. All Rights Reserved.

VERA-CS – CASL Advanced Core Simulator

- VERA-CS, the core simulator of VERA, relies on coupled neutronics, thermal-hydraulics and fuel temperature components:
  - MPACT provides 3D neutron transport capabilities
  - COBRA-TF subchannel code, provides TH and fuel temperature models

- MPACT 3D solution is obtained with a 2D-1D approach:
  - 2D Methods of the Characteristics (MOC) with SP3 for the axial coupling
  - Cross section from a 56-group microscopic cross section library
  - Capable of generating sub-pin level power distributions with actual detailed geometrical configuration of the fuel components (pellet, cladding etc.)
  - “One-step” process with no a priori homogenization or group condensation for the core spatial solution

- VERA-CS is still under active development
  - Successfully applied to modelling Startup Physics Tests for commercial PWRs
  - Being applied to cycle depletion analyses

© 2014 Westinghouse Electric Company LLC. All Rights Reserved.

VERA-CS vs. Current Practice

Physics Model	Industry Practice	VERA-CS
Neutron Transport	3-D diffusion (core) 2 energy groups (core) 2-D transport lattice calculations	3-D transport ~50 energy groups actual core conditions
Power Distribution	nodal average with pin-power reconstruction	explicit pin-by-pin
Thermal-Hydraulics	1-D assembly-averaged	subchannel (w/crossflow)
Fuel Temperatures	nodal average	pin-by-pin (r,z)
Depletion	infinite-medium cross sections history corrections spectral corrections reconstructed pin exposures	pin-by-pin with actual core conditions
Target Platforms	Workstation	Industry Class Platform (~1,000 cores)

© 2014 Westinghouse Electric Company LLC. All Rights Reserved.

Monte-Carlo Capabilities in VERA

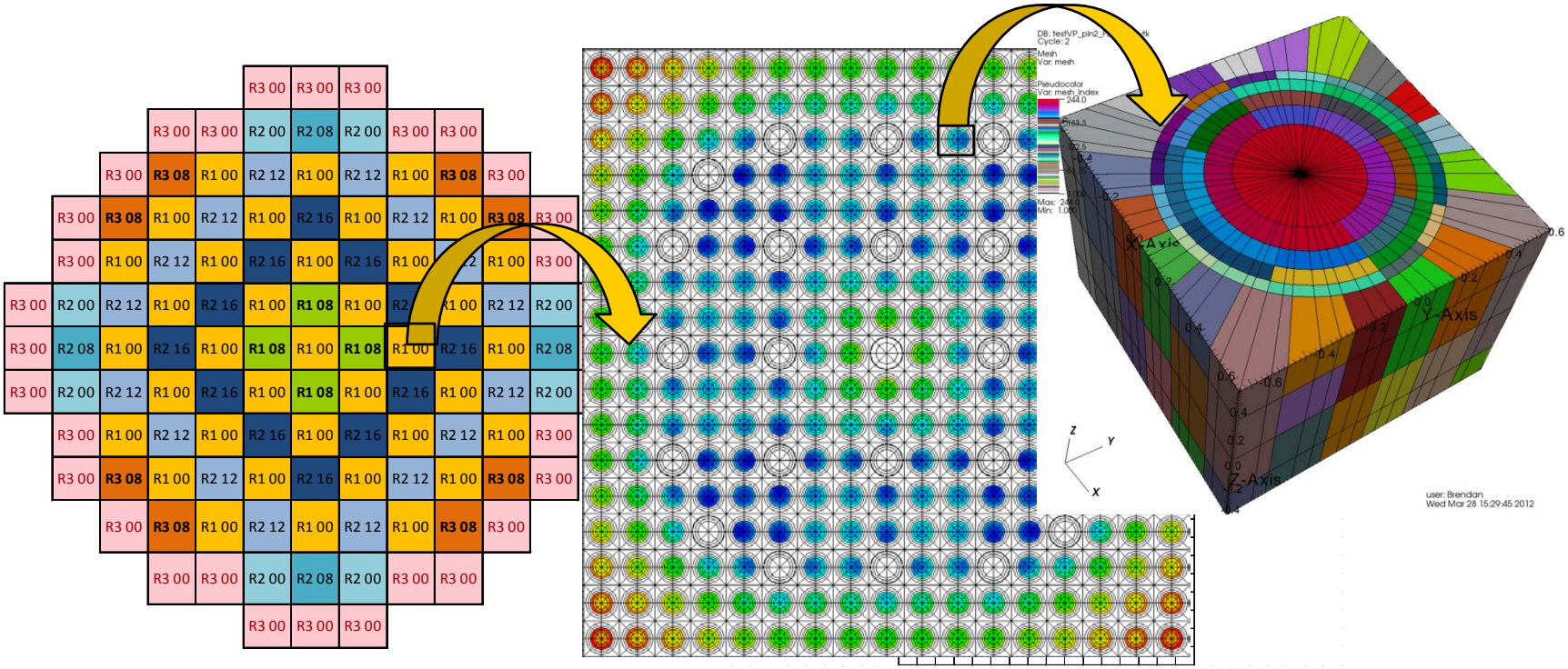
- VERA also has stochastic neutron transport capabilities with the SHIFT code
  - General purpose radiation transport code
  - Eigenvalue as well as fixed source calculations
  - Physics, tallies, geometry, source definitions, parallel decomposition, and variance reduction.
  - **Continuous energy data from the SCALE code package**
  - Multiple-Set-Overlapping-Domain parallel scheme to allow full domain replication, domain decomposition, and domain decomposition with overlap and multiple sets.
  - **Linear strong scaling behavior out to ~250,000 cores on the Oak Ridge Leadership Computing Facility TITAN machine has been demonstrated**

- In VERA, SHIFT is used as an advanced benchmarking tool of the deterministic component
  - Detailed power distribution especially

© 2014 Westinghouse Electric Company LLC. All Rights Reserved.

Krsko Startup Core Description

- 1876 MWt Core ~12-mo Cycle (now 1994 MWt 18-mo cycle)
- 121 Assemblies, 12-ft fuel with Inconel/SS Grids/Sleeves
- 3-Region first core (2.1, 2.6 3.1 U-235 w/o) with Pyrex BPs
- 16x16 Fuel Lattice – H/U ~ 3.6



© 2014 Westinghouse Electric Company LLC. All Rights Reserved.

Simulations Performed

- VERA deterministic (MPACT) and stochastic (SHIFT) neutron transport tools applied to Krsko start-up core analysis

- Power distribution comparisons (MPACT vs. SHIFT)
  - 2D Lattices
  - 2D Radial Core slice
  - 3D Assembly
  - 3D Full-Core calculations
  - Very “large” MC simulations (up to 2T particles for full-core)

- Startup Physics Tests (codes vs. measurements)
  - HZP Critical Configurations
  - Rod Worth
  - Boron Worth
  - Isothermal Temperature Coefficient

© 2014 Westinghouse Electric Company LLC. All Rights Reserved.

2D Lattice Results

	SHIFT (Monte Carlo)	MPACT (Deterministic)			
2D Lattices	k	Δk	RMS ΔP	Max ΔP	Hot Spot
Reg. 2 16 Pyrex	1.07204	-227	0.14 %	0.31 %	-0.21 %

SHIFT runs: 1 B total particle histories. 2h30 min execution time on 256 cores (~650 core-hours)

Delta pin power 100*(MPACT-SHIFT)

-0.21	-0.14	-0.12	-0.08	-0.07	-0.10	-0.05	-0.09	-0.10	-0.06	-0.07	-0.04	-0.11	-0.14	-0.16	-0.18
-0.17	-0.11	-0.03	-0.01	0.00	0.15	-0.03	-0.07	-0.02	-0.03	0.20	-0.04	0.00	-0.09	-0.10	-0.18
-0.10	-0.04	0.06	0.23	0.15	Px	0.06	-0.16	-0.05	0.09	Px	0.22	0.26	0.01	-0.02	-0.08
-0.07	0.09	0.25	Px	0.25	0.21	-0.15	GT	-0.21	-0.01	0.31	0.26	Px	0.23	0.03	-0.04
-0.07	0.03	0.26	0.23	0.09	0.17	-0.08	-0.15	-0.11	-0.01	0.23	0.14	0.27	0.22	0.04	-0.03
-0.06	0.17	Px	0.28	0.18	Px	0.14	-0.06	-0.06	0.12	Px	0.21	0.24	Px	0.23	-0.03
-0.10	0.04	0.12	0.05	0.01	0.10	-0.05	-0.20	-0.07	-0.04	0.13	-0.02	-0.11	0.12	-0.02	-0.03
-0.11	-0.09	-0.03	-0.16	-0.03	-0.09	-0.22	IT	-0.26	-0.08	-0.09	-0.18	GT	-0.20	-0.09	-0.08
-0.12	-0.14	-0.19	GT	-0.18	-0.05	-0.07	-0.22	-0.15	-0.08	-0.01	-0.04	-0.17	-0.10	-0.06	-0.10
-0.13	-0.09	0.05	-0.16	-0.04	0.12	0.01	-0.05	-0.10	0.00	0.09	0.00	-0.03	0.12	0.02	-0.08
-0.08	0.13	Px	0.24	0.18	Px	0.08	-0.05	-0.08	0.06	Px	0.22	0.24	Px	0.17	-0.03
-0.10	0.01	0.21	0.25	0.06	0.15	-0.03	-0.09	-0.16	-0.01	0.16	0.10	0.25	0.20	0.04	-0.05
-0.11	0.00	0.24	Px	0.24	0.29	0.03	-0.14	GT	-0.13	0.27	0.24	Px	0.28	0.08	-0.05
-0.13	-0.07	0.02	0.27	0.23	Px	0.10	-0.10	-0.21	0.07	Px	0.24	0.27	0.02	-0.06	-0.10
-0.14	-0.09	-0.01	0.10	0.02	0.15	0.00	-0.11	-0.07	-0.03	0.15	0.01	0.00	-0.08	-0.08	-0.12
-0.23	-0.17	-0.08	-0.05	-0.07	-0.09	-0.12	-0.18	-0.14	-0.16	-0.06	-0.11	-0.05	-0.09	-0.19	-0.17

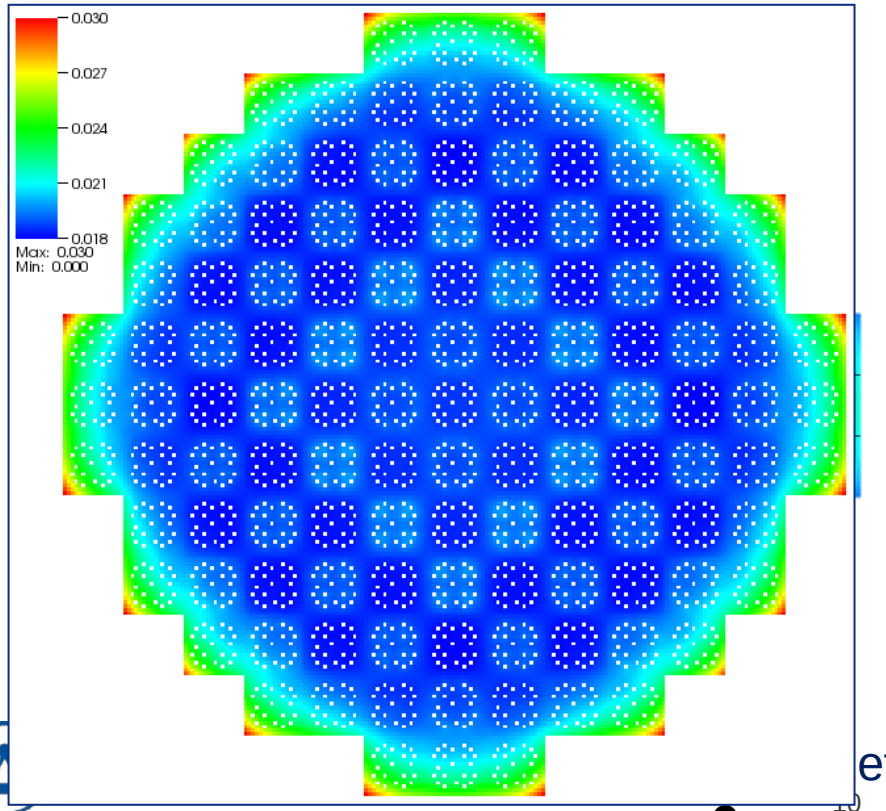
© 2014 Westinghouse Electric Company LLC. All Rights Reserved.

2D Core Results

	SHIFT (MC)	MPACT (Deterministic)			
	k	Δk	RMS ΔP	Max ΔP	Hot Spot
2D Core with Reflector	1.01214	-74	0.41%	1.19%	0.04%

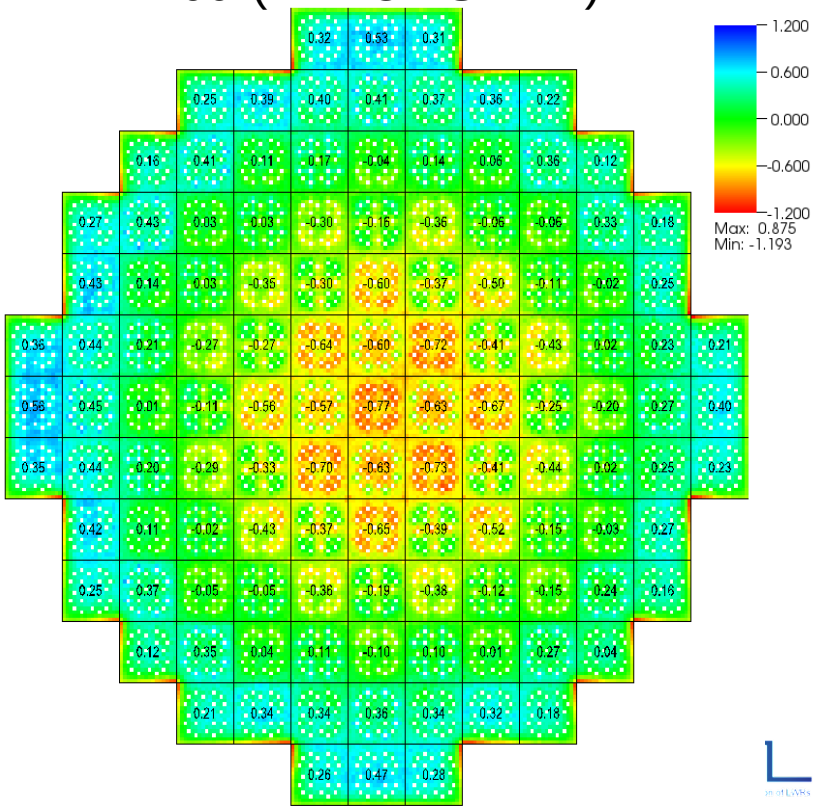
SHIFT runs: 100B total particle histories. 80 min execution time on 50,000 cores (60,000 core-hours)

Pin power uncertainty (SHIFT)



Pin power (SHIFT)

Delta pin power
100*(MPACT-SHIFT)

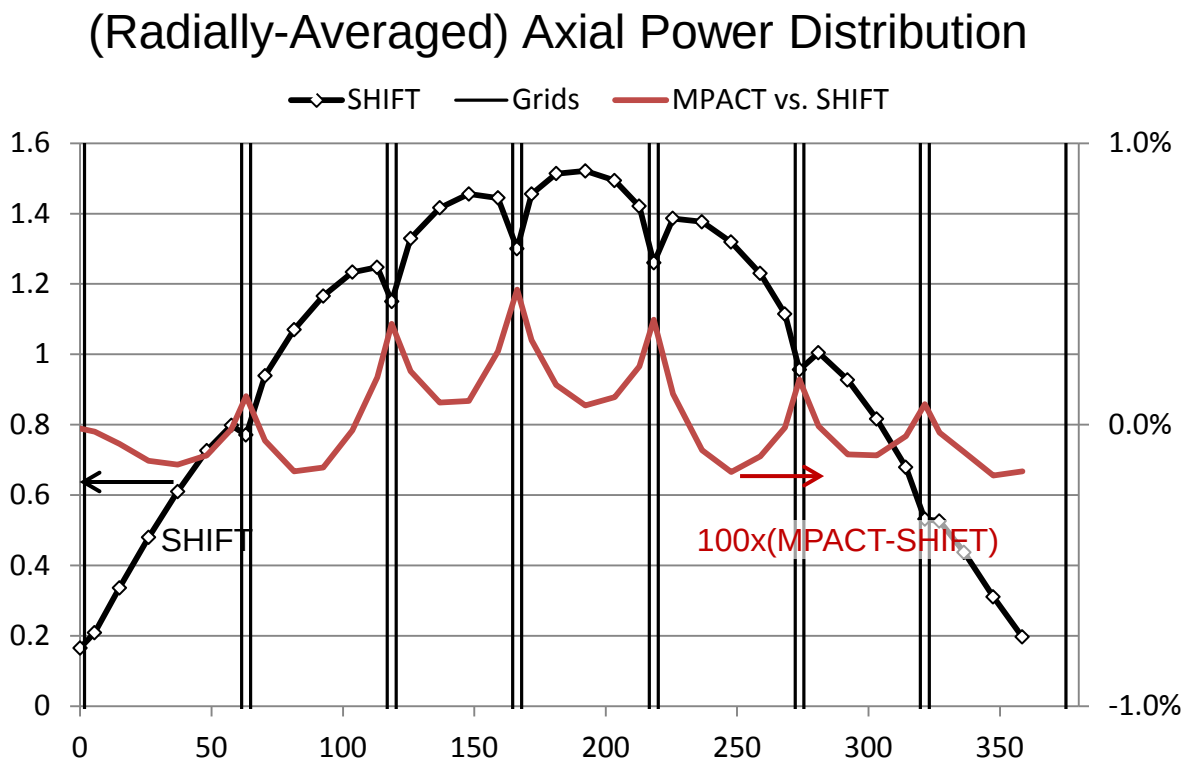


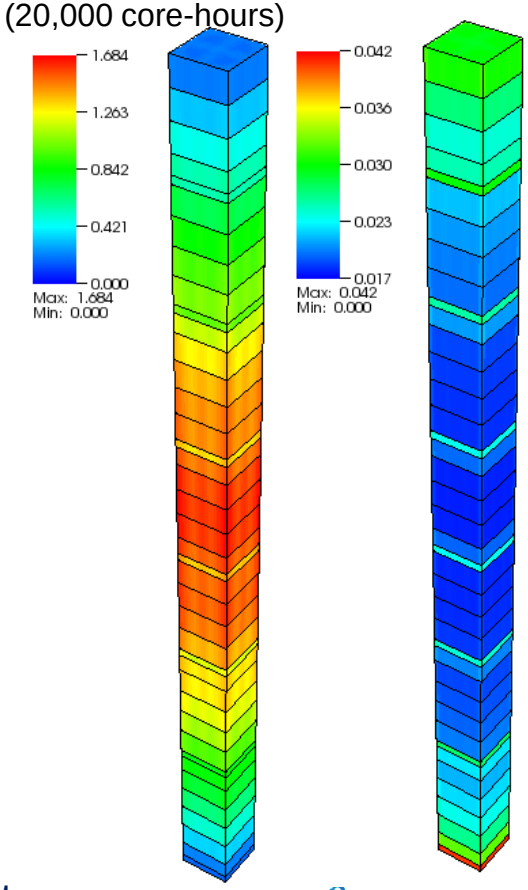
© 2014 Westinghouse Electric Company LLC. All Rights Reserved.

3D Assembly Results

	SHIFT (MC)	MPACT (Deterministic)			
	k	Δk	RMS ΔP	Max ΔP	Hot Spot
3D Assembly Reg. 2, 16 Pyrex	0.99698	-165	0.24	0.91	-0.24

SHIFT runs: 100B total particle histories. 48 min execution time on 25,000 cores (20,000 core-hours)





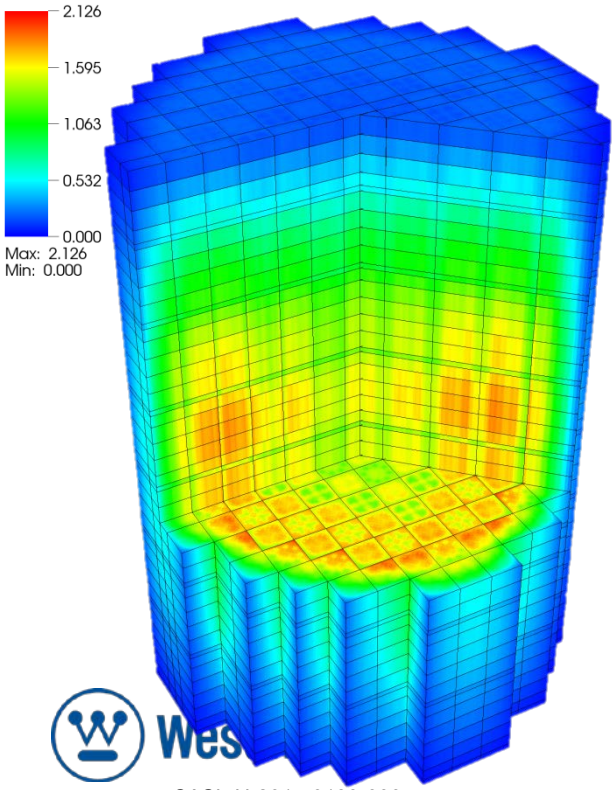
© 2014 Westinghouse Electric Company LLC. All Rights Reserved.

3D Core Results – All Rods Out

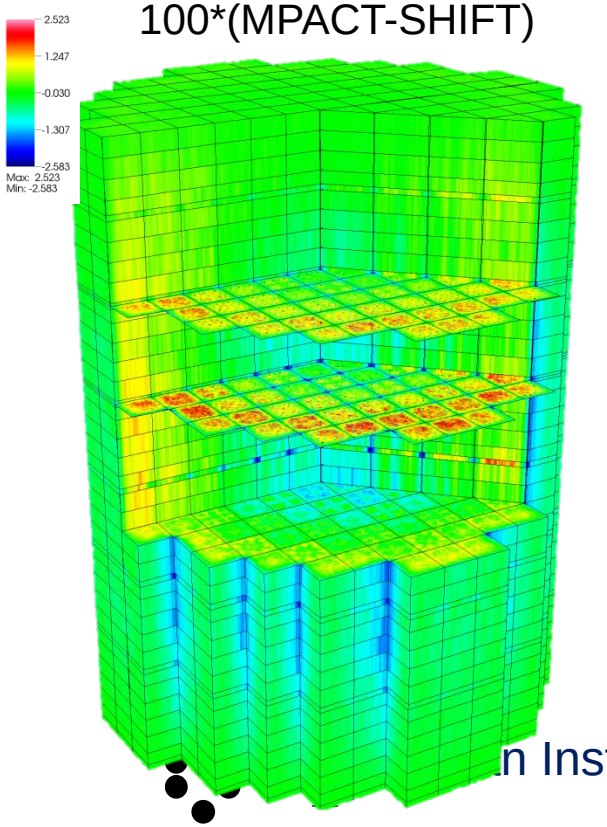
	SHIFT (MC)	MPACT (Deterministic)			
	k	Δk	RMS ΔP	Max ΔP	Hot Spot
3D Core All-Rods-Out	1.00051	-72	0.45 %	1.92%	-0.15%

SHIFT runs: 500B total particle histories. 2hr40m execution time on 125,000 cores. (~330,000 core hours)

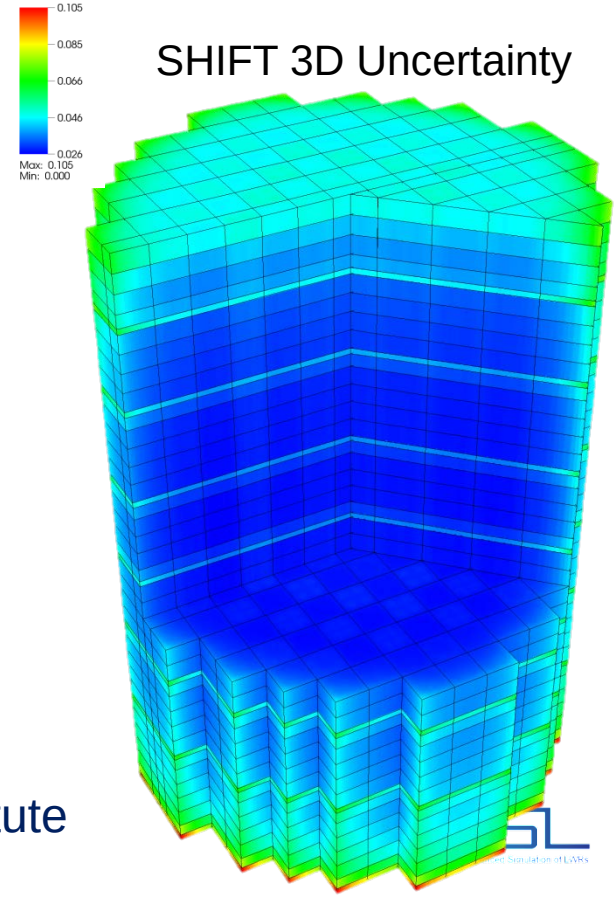
SHIFT 3D Power



Delta power
100*(MPACT-SHIFT)



SHIFT 3D Uncertainty



© 2014 Westinghouse Electric Company LLC. All Rights Reserved.

HZP Numerical Benchmarks – Summary Results

	SHIFT (Monte Carlo)	MPACT (Deterministic)			
2D Lattices	k	Δk	RMS ΔP (%)	Max ΔP (%)	Hot Spot (%)
Reg. 1 No Pyrex	1.24247	-315	0.06	0.17	-0.10
Reg. 2 No Pyrex	1.29374	-304	0.07	0.18	-0.14
Reg. 2 16 Pyrex	1.07204	-227	0.14	0.31	-0.21
Reg. 2 16 Pyrex SB@1500 ppm	0.95472	-141	0.13	0.31	-0.17
Reg. 3 No Pyrex	1.33047	-304	0.08	0.21	-0.19
Reg. 3 8 Pyrex	1.21684	-260	0.09	0.23	-0.17
3D Assembly Reg. 2, 16 Pyrex	0.99698	-165	0.24	0.91	-0.24
2D Core with Reflector	1.01214	-74	0.41	1.19	0.04
3D Core All-Rods-Out	1.00051	-72	0.45	1.92	-0.15
3D Core D+C Banks In	1.00142	-105	0.45	1.94	0.41
3D Core D+C+B+A Banks In	1.00018	-136	0.47	2.90	-0.85

SHIFT Reported Uncertainties (1 sigma). 3D core calculations are 500B-2T particle jobs

- Δk: < ± 5 pcm
- RMS ΔP : < ± 0.03%
- Max ΔP : < ± 0.04%
- Hot Spot: < ± 0.03%

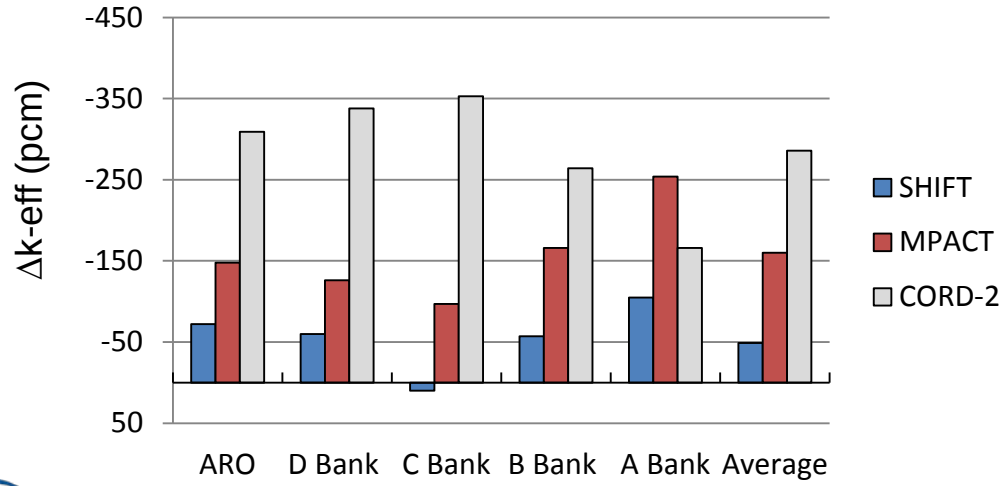
© 2014 Westinghouse Electric Company LLC. All Rights Reserved.

Startup Tests – HZP Critical Configurations

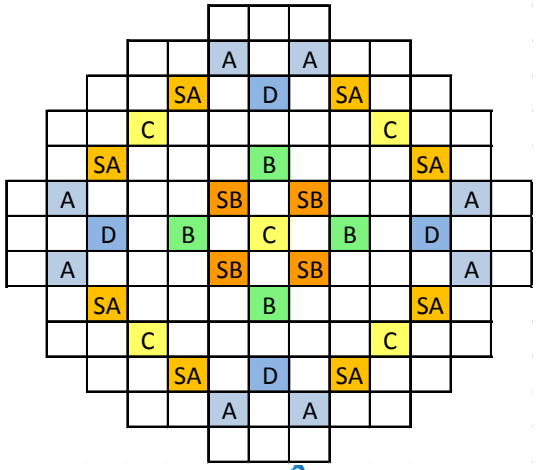
	Boron Endpoint (ppm)	SHIFT Δk-eff (pcm)	MPACT Δk-eff (pcm)	CORD-2 Δk-eff (pcm)
ARO	1445	-72	-144	-309
D Bank	1343	-60	-126	-338
C Bank (D Bank in)	1192	10	-97	-353
B Bank (DC Banks in)	1108	-57	-166	-264
A Bank (DCB Banks In)	905	-105	-254	-166
Average		-49	-160	-286

CORD-2 is JSI core physics package, validated and applied for Krsko reload analysis

Δk-eff (pcm) for Critical Configurations



Krsko Control Bank Configuration (Ag-In-Cd RRCAs)

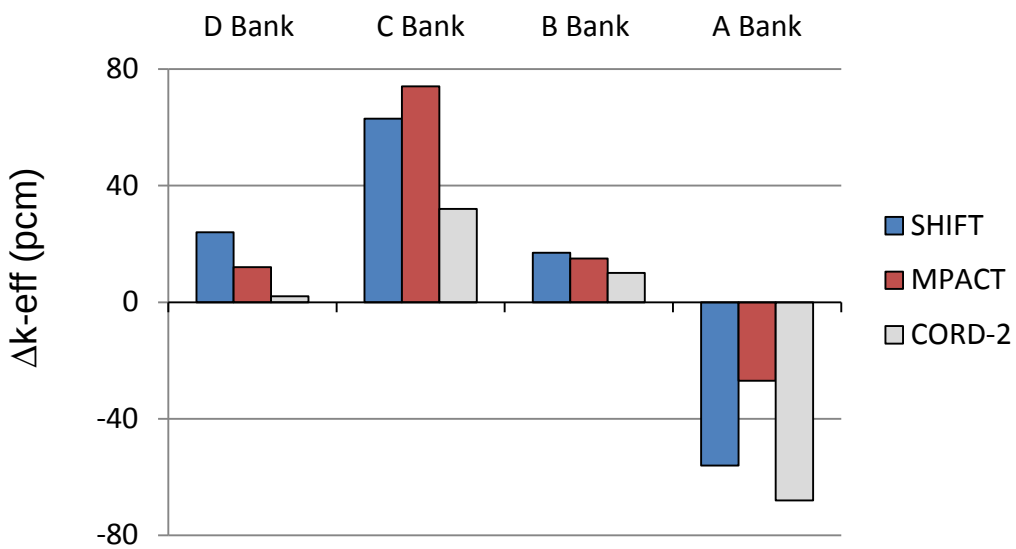


© 2014 Westinghouse Electric Company LLC. All Rights Reserved.

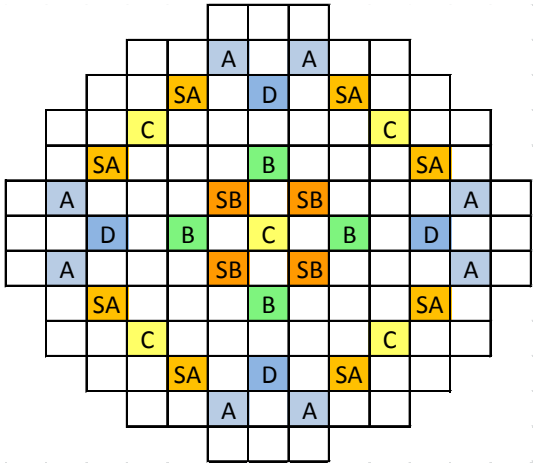
Startup Tests – Control Rod Worth

	Measured Rod Worth	SHIFT Δk-eff pcm	SHIFT Δk-eff %	MPACT Δk-eff pcm	MPACT Δk-eff %	CORD-2 Δk-eff pcm	CORD-2 Δk-eff %
D Bank	949	24	2.5%	12	1.3%	2	0.2%
C Bank (D Bank in)	1367	63	4.6%	74	5.4%	32	2.3%
B Bank (DC Banks in)	872	17	1.9%	15	1.7%	10	1.1%
A Bank (DCB Banks In)	2091	-56	-2.7%	-27	-1.3%	-68	-3.3%

Δk-eff (pcm) for Critical Configurations



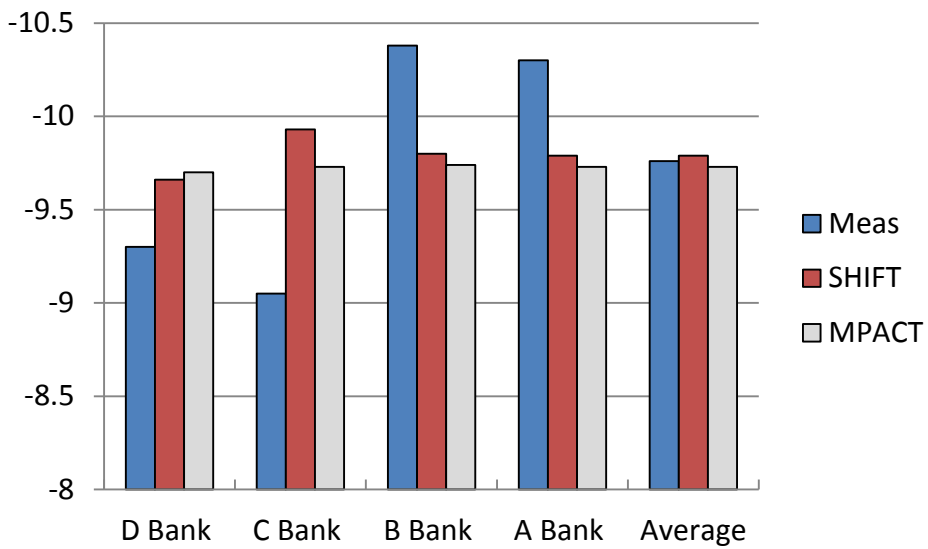
Krsko Control Bank Configuration (Ag-In-Cd RRCAs)



© 2014 Westinghouse Electric Company LLC. All Rights Reserved.

Startup Tests – Boron Worth

	Inferred Boron Worth (pcm/ppm)	SHIFT Boron Worth (pcm/ppm)	MPACT Boron Worth (pcm/ppm)
D Bank	-9.30	-9.66	-9.70
C Bank (D Bank in)	-9.05	-9.93	-9.73
B Bank (DC Banks in)	-10.38	-9.80	-9.74
A Bank (DCB Banks In)	-10.30	-9.79	-9.73
Average	-9.76	-9.79	-9.73



© 2014 Westinghouse Electric Company LLC. All Rights Reserved.

Startup Tests – Isothermal Temperature Coefficient

	Measured	SHIFT	MPACT	CORD-2	ANC
ITC (pcm/F) at the ARO Measured Critical Boron (1445 ppm of B)	-2.76	NA	-4.31 (-1.55)	-1.88 (+0.88)	-3.37 (-0.61)

© 2014 Westinghouse Electric Company LLC. All Rights Reserved.

Conclusions

- CASL VERA-CS applied to the analysis of the startup core of Krško in the framework of a Westinghouse-JSI-CASL collaboration
- Good agreement with measured data from deterministic (MPACT) and stochastic (SHIFT) CASL neutronic components
  - 50 and 160 pcm average deviations from criticality for SHIFT and MPACT over various critical configurations (ARO, Rodded)
  - Rod worth prediction mostly within 2% of the measured rod worth
  - 1.5 pcm/F deviation in the ITC (investigations underway)
  - Boron worth matches the measurement
- Predictions in line with JSI CORD-2 package which is validated and routinely applied for NPP Krško reload cores analysis
- Set of numerical benchmarks also performed with geometries up to 3D full-core, indicating excellent power distribution agreement between MPACT and SHIFT
- Future work include cycle depletion calculations and comparison to measurements

© 2014 Westinghouse Electric Company LLC. All Rights Reserved.

Acknowledgments

- This work was performed by a Westinghouse-CASL team in collaboration with the Jožef Stefan Institute (JSI) as part of a Joint Development Project between these institutions.

- The team is thankful to the NPP Krško personnel for the support during the project and permission to publish the measurement data provided.

- The authors would like to acknowledge John Turner (ORNL), CASL Chief Computational Scientist and the VERA-CS development team (MPACT developers Brendan Kochunas, Shane Stimpson and Aaron Graham from University of Michigan, and SHIFT developers Tara Pandya, Seth Johnson, Greg Davidson, from ORNL)

- This research was partially supported by CASL, an Energy Innovation Hub for Modelling and Simulation of Nuclear Reactors under U.S. Department of Energy Contract No. DE-AC05-00OR22725. (CASL: www.casl.gov ; Energy Innovation Hub: http://www.energy.gov/hubs)

- This research used resources of the Oak Ridge Leadership Computing Facility at ORNL, which is supported by the Office of Science of the U.S. DOE under Contract No. DE-AC05-00OR22725.

© 2014 Westinghouse Electric Company LLC. All Rights Reserved.

References

1. M. N. Avramova. CTF: A Thermal Hydraulic Sub-Channel Code for LWR Transient Analyses, User's Manual, Pennsylvania State University, February 2009.
2. A. T. Godfrey et al., "Simulation of Watts Bar Unit 1 Initial Startup Tests with Continuous Energy Monte Carlo Methods", PHYSOR 2014, Kyoto, Japan, September 28 – October 3, 2014
3. J.C. Gehin et al., "Watts Bar Unit 1 Cycle Zero Power Physics Tests Analysis with VERA-CS", PHYSOR 2014, Kyoto, Japan, September 28 – October 3, 2014.
4. F. Franceschini, et al., "**AP1000** PWR Reactor Physics Analysis with VERA-CS and KENO-VI – Part I: Zero Power Physics Tests", PHYSOR 2014, Kyoto, Japan, September 28 – October 3, 2014
5. F. Franceschini, et al., "**AP1000** PWR Reactor Physics Analysis with VERA-CS and KENO-VI – Part II: Power Distribution", PHYSOR 2014, Kyoto, Japan, September 28 – October 3, 2014
6. S. Palmtag et al., "Coupled Neutronics and Therma-Hydraulic Solution of a Full Core PWR Using VERA-CS", PHYSOR 2014, Kyoto, Japan, September 28 – October 3, 2014
7. B. Collins, S Stimpson, B Kochunas, T Downar, W Martin. "Assessment of 2D/1D Capability in MPACT". PHYSOR 2014, Kyoto, Japan, September 28 – October 3, 2014
8. B. Kelley, B Collins, E Larsen. 2D/1D approximations to the 3D neutron transport equation. II: Numerical comparisons. M&C 2013
9. S Stimpson, B Collins, T Downar. Axial Transport Solvers for the 2D/1D Scheme in MPACT. PHYSOR 2014. T.M. Evans et al., 2010. Denovo: A New Three-Dimensional Parallel Discrete Ordinates Code in SCALE. Nuclear Technology, 171, pp.171–200.
10. SCALE: A Comprehensive Modeling and Simulation Suite for Nuclear Safety Analysis and Design, ORNL/TM-2005/39, Version 6.1, June 2011. Available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-785.
11. J.C. Wagner, S.W. Mosher, T.M. Evans, D.E. Peplow, and J.A. Turner. Hybrid and Parallel Domain-Decomposition Methods Development to Enable Monte Carlo for Reactor Analyses. *Prog. Nuc. Sci. Tech*., **2**, 815--820, 2011.
12. M. Kromar, F. Franceschini, "Reactor Physics Analysis of the Krško NPP by JSI and Westinghouse", Proceedings of the International Conference Nuclear Energy for New Europe, Portorož, Slovenia, September 8 – 11, 2014