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Simulation of the NPP KRSKO Startup Core with CASL Core Simulator, VERA-CS

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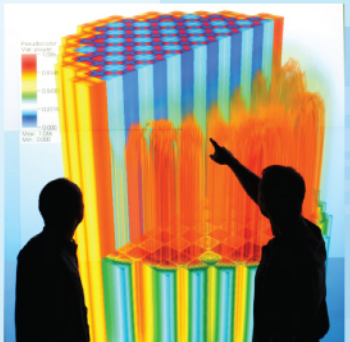

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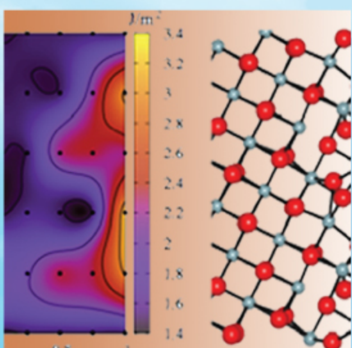

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ABSTRACT

This paper describes the application of the Virtual Environment for Reactor Applications (VERA) core simulator (VERA-CS) under development by the Consortium for Advanced Simulation of Light Water Reactors (CASL), to the core physics analysis of the Krško NPP. VERA-CS aims at enabling whole-core fuel cycle depletion deterministic transport analysis with subchannel thermal-hydraulic coupling. VERA-CS can also perform stochastic neutron transport calculations through a continuous-energy massively parallel Monte-Carlo code. This paper is focused on the application of VERA-CS deterministic and stochastic neutronic components to the analysis of the startup physics tests for the initial core of Krško. The results show good agreement with the startup physics tests measurements, as well as with predictions from the JSI CORD-2 package, which is validated and routinely used for the verification of the NPP Krško reload cores. Several code-to-code numerical benchmarks are also performed with geometries from lattice up to full-core indicating a consistent and high-quality power distribution prediction from the two VERA-CS neutronic components. Achieving accurate, spatially detailed, core power distribution prediction capabilities is key in reproducing and understanding the phenomena challenging PWR operation, which is one of the goals of the CASL initiative, while the favourable comparison with measured parameters exhibited by VERA-CS continues to broaden its validation basis.

1 INTRODUCTION

The Consortium for Advanced Simulation of Light Water Reactors (CASL) was established in July 2010 for providing advanced modelling and simulation solutions for commercial nuclear reactors. The CASL team is a consortium that consists of ten core partners and 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 features an advanced core simulator, VERA-CS, with a deterministic neutron transport code coupled to a subchannel thermal-hydraulic code to provide high-fidelity cycle depletion simulation capabilities of nuclear reactor cores. VERA-CS also features a continuous-energy Monte-Carlo code, with a massively parallel architecture, that can be used to generate numerical reference solutions and gain further insights on the performance of the deterministic component.

Both deterministic and stochastic components are applied here to the analysis of the Krško PWR by a Westinghouse-CASL team in collaboration with the Jožef Stefan Institute (JSI). The initial focus is on the startup physics tests for the initial core, with results presented in the following. The Krško plant is a 2-loop Westinghouse PWR that began electricity production in 1981. The startup core had a rated thermal capacity of 1,876 MWt, and a 626 MWe gross electric power; currently the thermal rating is 1,994 MWt with 696 MWe gross electric power. The main features of the startup core and fuel design are presented in the following, preceded by an overview of VERA-CS and followed by the results of the simulations performed, including a comparison with the relevant measured data from the startup core.

2 VERA OVERVIEW

The collection of computational tools being developed by CASL and part of VERA includes neutronics, thermal-hydraulics, computational fluid mechanics, fuel performance and coolant chemistry components. In order to support the analysis of the steady-state operation of reactors, VERA includes the VERA-CS component that includes coupled neutronics, thermal-hydraulics and fuel temperature components with an isotopic depletion and decay capability. Two neutronics capabilities are currently available, one based on the Insilico Cartesian mesh Sn and SPn capability and the other based on MPACT using a Method of Characteristics approach, which is the primary method currently under development. The thermal-hydraulics and fuel temperature models are provided by the COBRA-TF subchannel code [1] being developed by CASL and Pennsylvania State University. The isotopic depletion is performed using the ORIGEN code system. While under active development, the core simulator has been applied to modelling Startup Physics Tests [2]-[5], hot full power configurations with fresh fuel [6], and depletion capability is being applied to model the first operating cycle of the Watts Bar Nuclear Plant Unit 1.

2.1 VERA-CS Deterministic Component (MPACT)

MPACT [1] is a three-dimensional (3-D) whole core transport code capable of generating sub-pin level power distributions. This feature is accomplished by obtaining the integral transport solutions to the heterogeneous reactor problem in which the actual detailed geometrical configuration of fuel components such as the pellet and cladding is modelled explicitly. The cross section data needed for the neutron transport calculation are obtained directly from a multigroup microscopic cross section library similar to those used in lattice physics codes. Hence MPACT involves neither a priori homogenization nor group condensation for the core spatial solution.

The 3D solution is obtained by means of a 2D-1D approach [7]-[8] which employs planar Methods of the Characteristics (MOC) solutions in the framework of the 3-D coarse mesh finite difference (CMFD) formulation. The axial coupling is resolved by one-dimensional (1-D) diffusion solutions and the planar and axial problems are coupled through the transverse leakage. The use of a lower order 1-D solution in the axial direction is justified when the axial heterogeneities are not significant. When strong axial heterogeneities are present, it is possible to use higher order methods in MPACT [9] such as 1-D SPN or SN kernels to improve the solution accuracy.

2.2 VERA Monte-Carlo Component (SHIFT)

SHIFT is a general purpose radiation transport code that performs stochastic modeling of particle physics using the Monte Carlo method. It can perform eigenvalue calculations as well as fixed source calculations for the given radiation transport problems. The main modules of SHIFT include physics, tallies, geometry, source definitions, parallel decomposition, and variance reduction.

The SHIFT physics package can use either multigroup or continuous energy data. All data is provided by the SCALE code package [10]. SHIFT uses the Multiple-Set-Overlapping-Domain (MSOD) parallel scheme [11] that allows full domain replication, domain decomposition, and domain decomposition with overlap and multiple sets. Using MSOD, SHIFT has demonstrated linear strong scaling behavior out to ~250,000 cores on the Oak Ridge Leadership Computing Facility TITAN machine.

3 KRSKO START-UP CORE DESCRIPTION

The Krsko core consists of 121 fuel assemblies arranged as shown in Figure 1. The loading pattern consists of a 3-region modified checkerboard, where the highest enriched Region 3 fuel, with a ^{235}U content of 3.1 w/o, occupies the core periphery, the lowest enriched Region 1 fuel, with a ^{235}U content of 2.1 w/o, is placed in the core central assemblies and it is alternated with the middle-enriched Region 2 fuel, at 2.6 w/o ^{235}U, in the intermediate core locations. The fuel assembly is based on the Westinghouse 16x16 fuel lattice design, with 235 fuel locations, 20 guide thimbles and 1 instrumented thimble.

The fuel active height is 144-in and encompasses a bottom grid and 6 mid grids, with a top grid outside of the active fuel height. The grids are made of Inconel with type 304 stainless steel sleeves. The presence of stronger neutron absorbers in Inconel and stainless steel leads to a larger flux depression in correspondence of the grids compared to Zr-based grids. The clad is Zircaloy-4 with an outside diameter (OD) of 0.374 in, and a pellet OD of 0.3225 in; the fuel pitch is 0.485 in. This results in an H/U of ~3.6 and to a lower moderated lattice than other typical designs, e.g. ~ 4.0 for Westinghouse standard 17x17 fuel. This drier lattice and the ensuing harder spectrum lead to increased ^{238}U reasonance absorptions and higher Pu production, which can introduce some challenges to the self-shielding methods adopted in typical lattice codes. The core features 33 Reactivity Control Cluster Assemblies (RCCA) arranged in 7 banks (A, B, C and D with the shut-down banks SA and SB); Ag-In-Cd is used as the neutron absorber material. The RCCA locations and bank assignment are shown in Figure 2. Burnable poison inserts, containing Pyrex glass with 12.5 w/o B_2O_3, are used for reactivity hold-down and power shaping. Fuel assemblies featuring 8, 12 and 16 Pyrex rods are employed in the startup-core.

4 SIMULATIONS PERFORMED

The simulations performed with VERA for the Krško startup core configuration are summarized below. All simulations have been performed at HZP (557 °F) conditions, except the 2D lattice simulations which were performed at 600 K.

- 2D lattice
- 2D core slice at the core axial midplane, including the core baffle in the radial reflector region
- 3D assembly, including the grids and the neutronically relevant structure above and below the fuel. The specific assembly modeled is Region 2 fuel with 16 Pyrex rods
- 3D full-core Zero Power Physics Tests (ZPPTs) simulations: HZP All-Rods-Out critical boron, rod worth, isothermal temperature coefficient (ITC) and boron worth (BW)

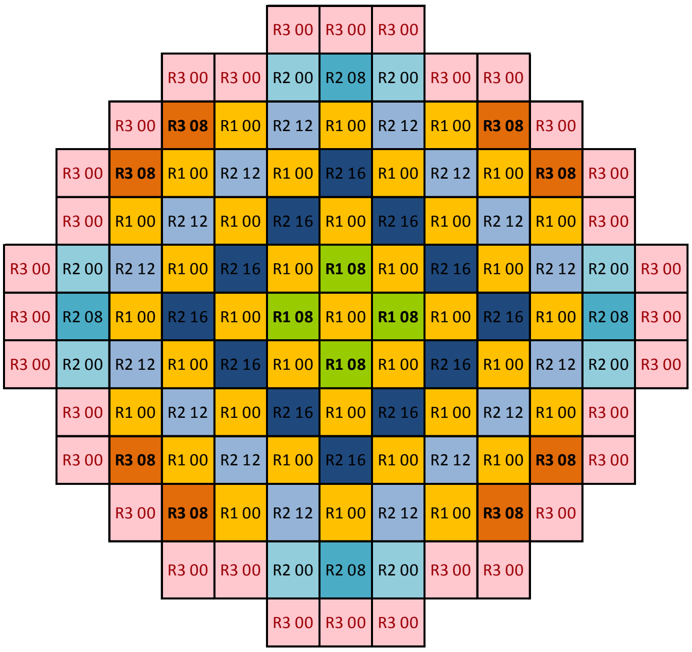

Figure 1: Krško startup core loading pattern (Reg. # - # of Pyrex Inserts shown)

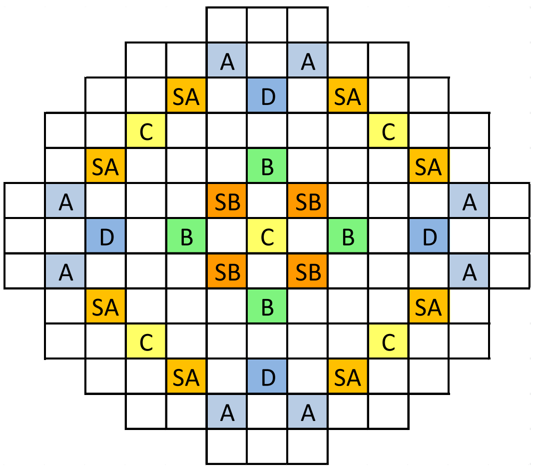

Figure 2: Krško RCCA locations (Control Bank ID shown)

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5 RESULTS

5.1 2D Lattice

The key results from the lattice simulations performed, summarized in Table 1, show good reactivity agreement betweeen SHIFT and MPACT, and remarkable power (or fission rate) distribution agreement. Overall SHIFT predicts a slightly higher reactivity than MPACT, 300 pcm for lattices without Pyrex, and ~150-200 for the Pyrex (and soluble boron) lattices. The reduction in delta reactivity when Pyrex are present in the model may be attributable to some favorable compensation of errors. The power distribution comparison between MPACT and SHIFT indicates remarkable agreement, with RMS in the 0.05-0.15% range and maximum differences in the 0.2-0.3% range across the lattices analyzed, with the larger differences pertaining to the Pyrex configurations.

Table 1: Summary Lattice Results MPACT vs. SHIFT

	SHIFT (2)	MPACT		
	k-inf	Δk-inf	RMS(3) ΔP (%)	Max(4) ΔP (%)
Reg. 1 No Pyrex	1.24247	-315	0.06	0.17
Reg. 2 No Pyrex	1.29374	-304	0.07	0.18
Reg. 2 16 Pyrex	1.07204	-227	0.14	0.31
Reg. 2 16 Pyrex SB (1)	0.95472	-141	0.13	0.31
Reg. 3 No Pyrex	1.33047	-304	0.08	0.21
Reg. 3 8 Pyrex	1.21684	-260	0.09	0.23

(1) SB: Soluble boron at 1500 ppm. 600K fuel and coolant temperature conditions

(2) SHIFT MC parameters: 1.1B total particle histories, 1M particles/generation, 1100 total generations with 100 inactive generations. Simulations performed in 2.5 hr on 256 cores (635 core hours). k-eff uncertainty of 5 pcm

(3) RMS ΔP is the Root Mean Square of the delta pin power for MPACT vs. SHIFT over the lattice.

(4) Max (absolute) ΔP for MPACT vs. SHIFT over the lattice.

5.2 2D Core

Table 2 summarizes the results of the simulations performed for the 2D core slice. SHIFT predicts ~ 180 pcm higher reactivity, in line with the lattice results. The power distribution from SHIFT is shown in the top half of Figure 3, with the delta power MPACT vs. SHIFT shown in the bottom half. While a slight power tilt between the codes exists, with MPACT underprediciting the power at the core center and ovepredicting it at the periphery, the comparison shows overall good agreement. This is reflected in the 0.4 % ΔP RMS and 1.2 maximum ΔP.

Table 2: Summary 2D Core Results MPACT vs. SHIFT

SHIFT (1,2)	MPACT			
k-inf	Δk-inf (pcm)	ΔP RMS (%)	Max ΔP (%)	Limiting Pin ΔP (%)
1.01214	-74	0.41	1.19	0.04

(1) Soluble boron at 1445 ppm. HZP temperature conditions (557 F)

(2) SHIFT MC parameters: 100B total particle histories, 500 M particles/generation, 2000 total generations with 250 inactive generations. k-eff uncertainty of 5 pcm. CPU resources: 50,000 cores, 1.2 hr execution time (~60,000 core-hours)

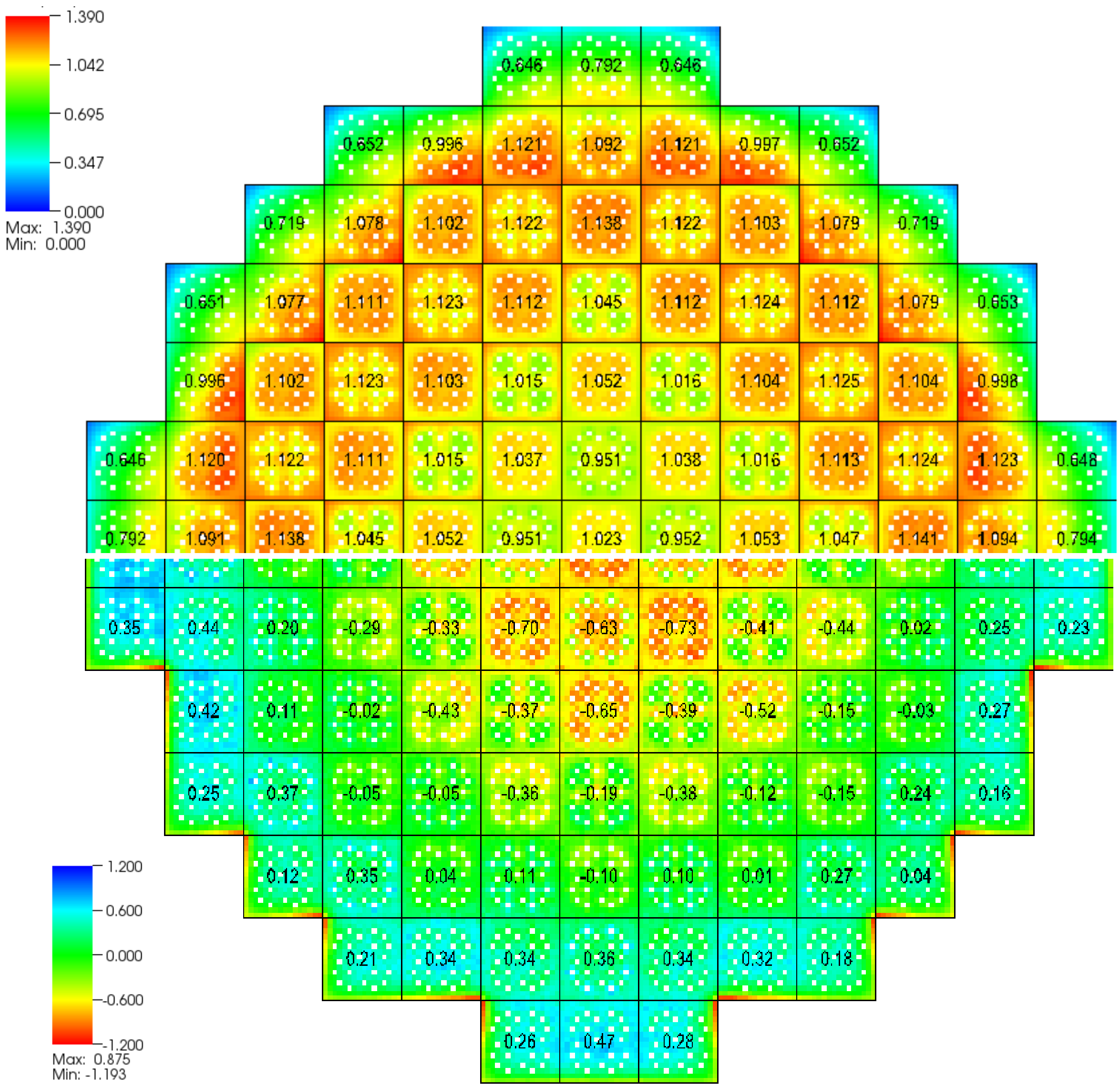

Figure 3: 2D Core Pin Power– SHIFT (top half) and MPACT vs. SHIFT (bottom half)

5.3 3D Assembly

Table 3 summarizes the key results for the 3D assembly; specifically the Region 3 fuel assembly with ^{235}U at 2.6 w/o and 16 Pyrex rods is modelled. The delta k-eff between MPACT vs. SHIFT is ~-180 pcm, with a delta Axial Offset (AO) of ~ 0.3% and a ΔP RMS of ~0.4%. The maximum ΔP observed for the entire model is ~1.9%. The ΔP at the hot spot is ~0.5%.

Figure 4 shows a good agreement in axial power distribution with a slight deterioration in correspondence of the grids. The reason for this is attributed, at least in part, to the different grid representation between the codes, and developments are underway that should improve this aspect of the comparison.

Table 3: Summary Assembly Results MPACT vs. SHIFT

SHIFT[1,2]		MPACT				
k-eff	AO (%)	Δk-eff	ΔAO (%)	RMS[3] ΔP (%)	Max[3] ΔP (%)	Hot Spot[3] ΔP (%)
0.99698	-0.46	-177	-0.32	0.42	1.86	-0.52

(1) Soluble boron at 900 ppm. HZP temperature conditions (557 F)
(2) SHIFT MC parameters: 100B total particle histories, 500M particles/generation, 2,000 total generations with 250 inactive generate ions. k-eff uncertainty of 2 pcm. CPU resources 0.8 hr execution time, 25,000 cores, ~20,000 core-hours
(3) The metrics for the power comparison (RMS, Max and Hot Spot) are calculated over a 16x16x48 mesh structure (16x16 radial pins and 48 axial layers with explicit representation of the fuel grids)

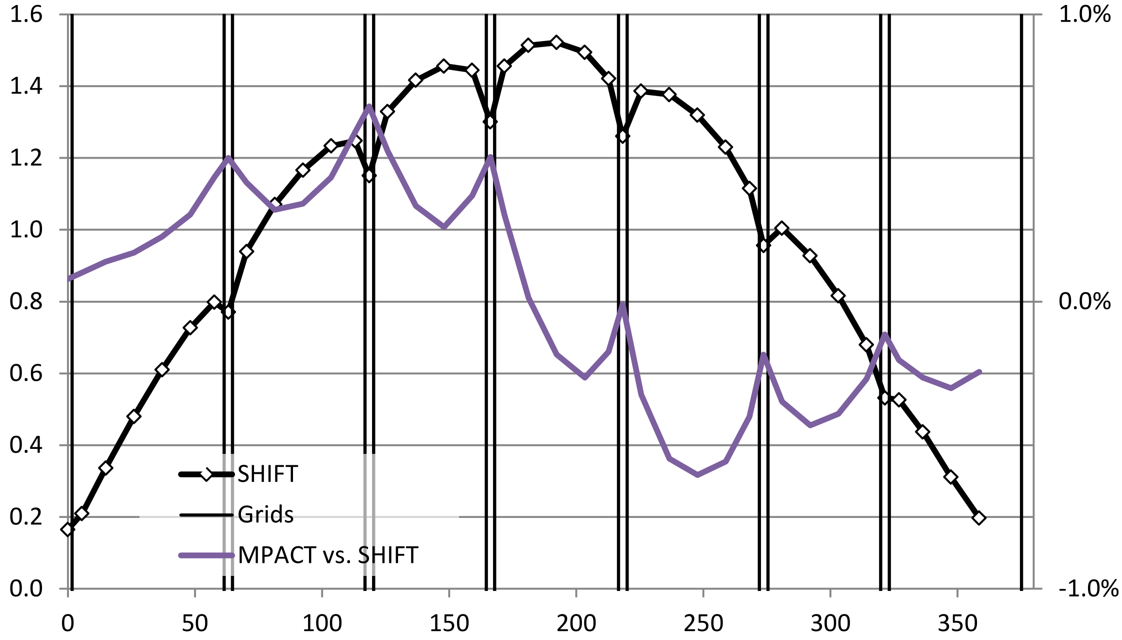

Figure 4: 3D Assembly Axial Power MPACT vs. SHIFT

5.4 3D Core

Table 4 summarizes the results of full-core 3D simulations with the two codes. The Δk-eff is ~ 70 pcm with ~0.1% ΔAO, ~0.5 ΔP RMS and 2.6% max ΔP. The results of this simulation are consistent with the trends observed for the 2D core and 3D assembly simulations already discussed. It should be noted the magnitude of this simulation using the VERA Monte-Carlo capabilities from SHIFT, with 500 billion total particle histories for a simulation time of less than 3 hours on 125,000 cores, thanks to the highly parallel feature of the code. This capability to perform massive Monte-Carlo simulations with a relatively simple input and in a relatively short time, enables to quickly establish reference numerical solutions for a variety of large geometries, up to full-core of commercial LWRs, which is very advantageous for code validation and advanced benchmarking.

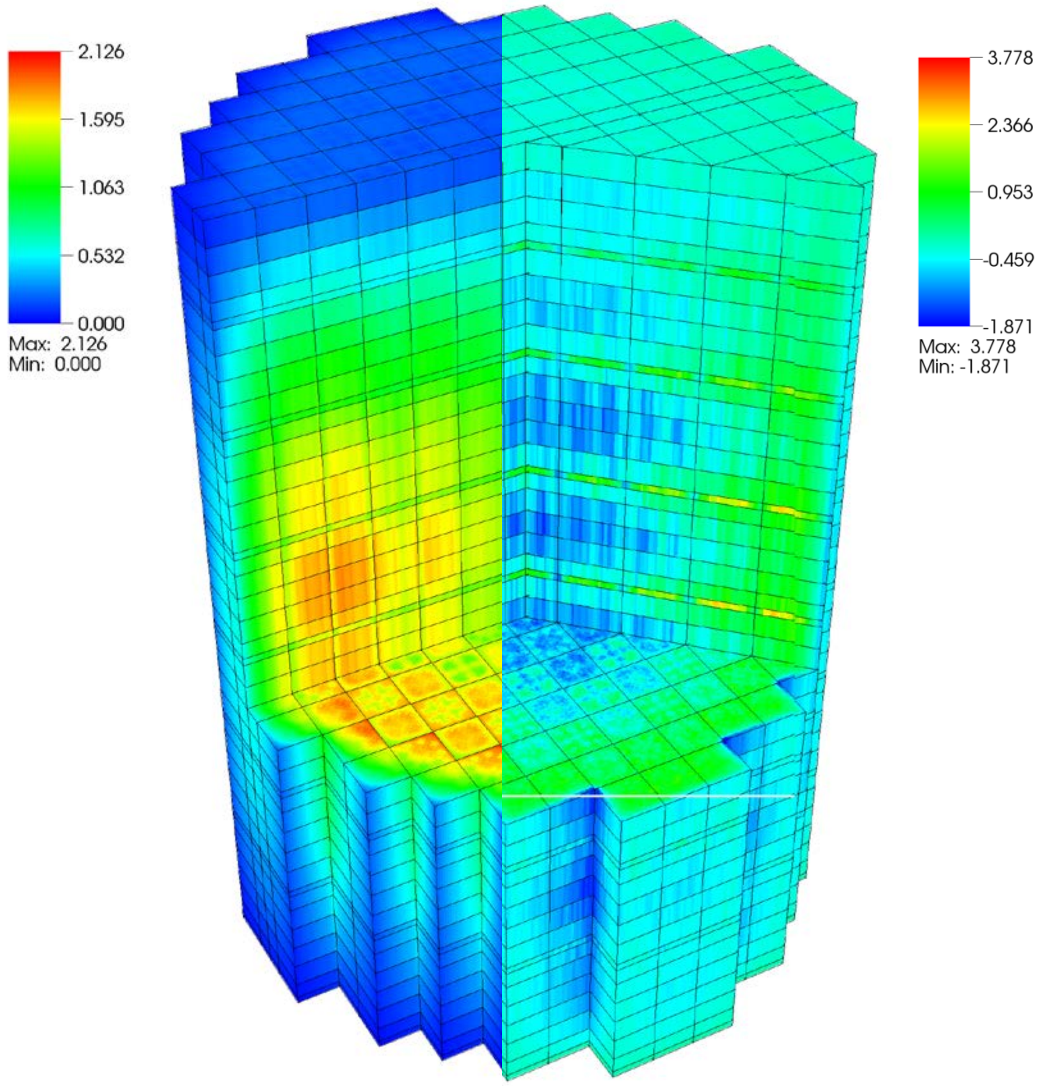

Figure 5: 3D Core Power Distribution from SHIFT (left-half of the picture) and % ΔP MPACT vs. SHIFT (right-half of the picture)

Table 4: Summary 3D Core Results MPACT vs. SHIFT

SHIFT(1,2)		MPACT				
k-eff	AO (%)	Δk-eff	ΔAO (%)	RMS ΔP (%)	Max ΔP (%)	Hot Spot ΔP (%)
1.00051	-0.66	-69	0.1	0.50	2.58	-0.14

(1) Soluble boron at 1445 ppm. HZP temperature conditions (557 F)

(2) SHIFT MC parameters: 500B total particle histories, 2.5B particles/generation, 2000 total generations with 500 inactive generations. k-eff uncertainty of 3 pcm. CPU resources 2hr40m execution time, 125,000 cores, ~336,000 core-hours

5.5 Start-up Physics Tests

The results obtained from VERA-CS for the Start-up Physics Tests simulations are reported in this section. Results from CORD-2, the code developed by the Reactor physics department of the Jožef Stefan Institute, are also added to the comparison. The CORD-2 system enables determination of the core reactivity and power distribution with a very computationally efficient architecture. This package has been validated for the nuclear design calculations of PWR cores and has been used for the verification of the NPP Krško reload cores since 1990. The results reported here are based on the work in [12]

Table 5 shows the predicted 3D core HZP k-eff from VERA, which is approximately -30 pcm from criticality for SHIFT and approximately -150 pcm for MPACT at the measured critical boron concentration (CBC) of 1445 ppm. Using the boron worth prediction from Table 8, this translates into a predicted HZP CBC of 1442 ppm for SHIFT and 1429 ppm for MPACT, respectively 3 ppm and 16 ppm lower than the measurement of 1445 ppm. The predicted HZP CBC from CORD-2 is 1477, ~32 ppm higher than the measured value.

The predicted Isothermal Temperature Coefficient from MPACT is -4.3 pcm/F, significantly more negative than the measured value of -2.8 pcm/F. This ITC bias has been observed also for other first cores simulations performed with VERA, and investigations are underway to resolve this issue. ITC simulations with the SHIFT code have not been performed at this time. The ITC prediction from CORD-2 is -1.9 pcm/F, at +0.7 pcm/F from the measured ITC.

The rod worth results reported in Table 6 show overall good agreement with the measured values from all codes employed. The largest difference of approximately 5% is observed for VERA when the D+C bank are inserted, with an approximately 3% difference for CORD-2 and SHIFT when D+C+B+A banks are inserted. The rod worth from the various codes in the remaining rod worth calculations is within 2% of the measured values.

Table 7 indicates the predicted eigenvalue at the boron endpoint for the various banks insertion, and for the ARO configuration, with good agreement with the expected criticality obtained for each configuration during the startup. The prediction from SHIFT is particularly close to criticality, with an average delta k-eff of approximately -50 pcm, vs. -160 pcm from MPACT and -290 pcm from CORD-2.

Table 8 indicates the calculated boron worth from SHIFT and MPACT vs. the inferred rod worth from the boron endpoints and measured rod worth. It can be seen that notwithstanding some variance in the inferred values for the various banks configuration, likely attributable to the uncertainty in the measured boron endpoint, the average inferred worth and calculated worth are in excellent agreement at approximately -9.8 pcm/ppm.

Table 5: Startup Results: HZP Criticality and ITC

	Measured	CORD-2	SHIFT [4]	MPACT
ARO – k-eff (cold) [1]	-		1.00098	0.99975
ARO – k-eff (hot) [2]	-		0.99968	0.99846
ARO – CBC [3] (ppm)	1445	1477	1442	1429
ITC (pcm/F)	-2.76	-1.88		-4.31

[1] All-Rods-Out (ARO) k-eff at cold dimensions (no thermal expansion applied)

[2] Thermal expansion applied as a -130 pcm reactivity bias assumed based on Westinghouse on-house core simulator results.

[3] Critical Boron Concentration (CBC) at HZP Conditions

[4] SHIFT MC parameters: 10B total particle histories, 10 M particles/generation, 1000 total generations with 300 inactive generations. Simulations performed on 10,000 cores in 42 min (~7,000 core hours). k-eff uncertainty of 5 pcm.

Table 6: Startup Results: Rod Worth

	Measured	CORD-2		SHIFT		MPACT	
	Rod Worth	Rod Worth	Δ Worth %	Rod Worth	Δ Worth %	Rod Worth	Δ Worth %
D Bank	949	951	0.2%	973	2.5	961	1.2
C Bank (D Bank in)	1367	1399	2.3%	1430	4.6	1441	5.4
B Bank (DC Banks in)	872	882	1.1%	889	2.0	887	1.7
A Bank (DCB Banks In)	2091	2023	-3.3%	2035	-2.7	2064	-1.3

Table 7: Startup Results: Boron Endpoint Criticality

	Boron(1) (ppm)	CORD-2	SHIFT		MPACT	
		Δk-eff	k-eff	Δk-eff	k-eff	Δk-eff
ARO	1445	-309	0.99968	-32	0.99846	-155
D Bank	1343	-338	0.99940	-60	0.99874	-126
C Bank (D Bank in)	1192	-353	1.00010	10	0.99903	-97
B Bank (DC Banks in)	1108	-264	0.99943	-57	0.998340	-166
A Bank (DCB Banks In)	905	-166	0.99895	-105	0.997462	-254
Average		-286		-49		-160

(1) Measured boron endpoint during the rod worth measurement with the boron dilution technique

Table 8: Startup Results: Boron Worth (BW)

	Inferred BW(1) (pcm/ppm)	SHIFT BW(2) (pcm/ppm)	MPACT BW(2) (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

(1) Calculated as the ratio of the delta in the measured boron endpoint before and after a given bank insertion and the measured rod worth for that bank

(2) Calculated as the delta in k-eff from a soluble boron perturbation, at a given bank insertion configuration, divided by the boron variation

6 CONCLUSIONS

The application of VERA-CS to the analysis of the startup physics tests for the initial core of Krško shows good agreement with the measured data from both the deterministic (MPACT) and stochastic (SHIFT) neutronic components of VERA-CS. The ARO CBC prediction from SHIFT is 3 ppm from the measured value, with a 16 ppm discrepancy for MPACT. The rod worth prediction from the two components is consistent and typically within 2% of the measured rod worth, with the largest rod worth difference observed of approximately 5%. The ITC calculation, performed at this time only with MPACT, reveals a approximately 1.5 pcm/F discrepancy with the measured value. Investigations are underway to understand the reason for this discrepancy. The eigenvalue over the range of rod configurations and boron endpoints of the startup tests indicates an average discrepancy of 50 pcm and 160 pcm from criticality for respectively SHIFT and MPACT, with maximum discrepancies of ~100 pcm and 250 pcm. These predictions are in line with those from the JSI CORD-2 package which has been validated for the nuclear design calculations of PWR cores and is used for the verification of the NPP Krško reload cores.

In addition to the Startup Physics Tests simulations, a set of numerical benchmarks has been performed with geometries from lattice up to 3D full-core. These benchmarks indicate a remarkable power distribution agreement between MPACT and SHIFT, with delta power RMS of <0.5% for all the cases analysed. Obtaining this accurate and spatially detailed (sub-pin) prediction of the 3D power distribution is key in reproducing and understanding the phenomena challenging PWR operation (like CRUD) that the CASL initiative has set forth to improve, while the favourable comparison with measured parameters and proven codes contribute to strengthen VERA validation basis.

Future work towards this effort will include cycle depletion calculations for the Krško start-up core and comparison to measurements, in order to evaluate the behaviour of VERA-CS, and in particular of its deterministic component, at at-power operating conditions.

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