Karlsruhe Institute of Technology

Determination of equilibrium cycles for reduced moderation BWR with PARCS and assessment safety parameters

INSTITUTE FOR NEUTRON PHYSICS AND REACTOR TECHNOLOGY (INR)
REACTOR PHYSICS AND DYNAMIC GROUP (RPD)

Markus T. Schlenker, Victor Sanchez, Robert Stieglitz
Karlsruhe Institute of Technology

CAMP 2013 Fall Meeting
Washington, DC
November 6 - 8, 2013

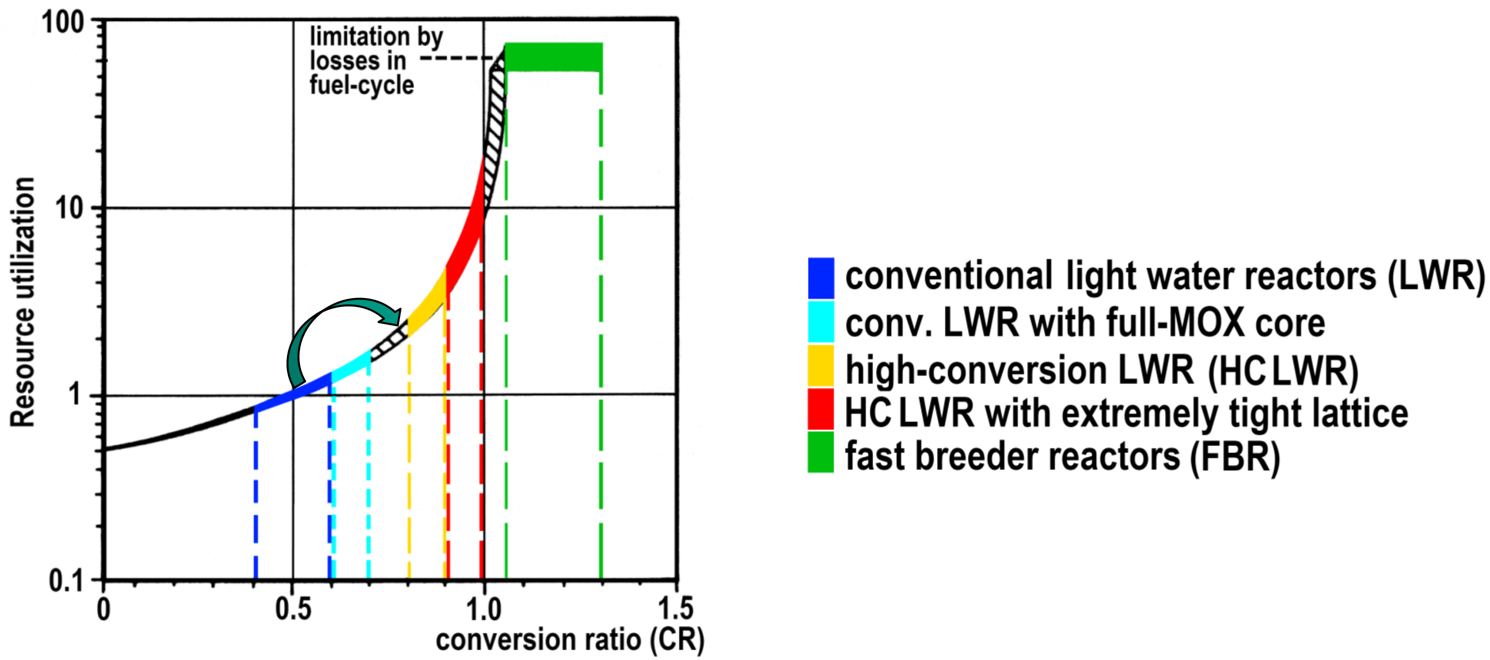
Outline

- Introduction
  - Motivation
  - Fuel Assembly Design
  - Cross Section Generation & Branch structure
  - Core Model & Cycle Definition
- Results for Equilibrium Cycle
  - Convergence of Multi-Cycle-Depletion Analysis
  - General Results
  - Reactivity Coefficients
  - Cold Shutdown Margin
- Conclusion
  - Summary
  - Outlook

INTRODUCTION

Motivation

- Increase the fuel utilization in well-known German Gen-II BWR type 72 by increasing the conversion ratio
- Keep safety parameters in acceptable range

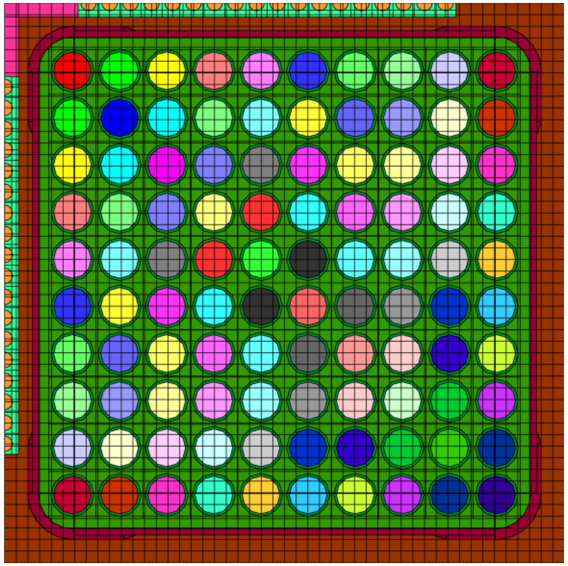


Selected Tools

- SCALE6.1 / TRITON lattice code
  - Few group homogenized cross section generation
- GenPMAXS cross section interface
  - SCALE-XS to PMAX
- PARCS / PATHS
  - PARCS: 3D reactor core simulator
    (hybrid nodal kernel used for investigations)
  - PATHS: steady-state thermal-hydraulic solver for BWR

Fuel Assembly Design

- Geometry changes starting from reference FA ATRIUM^{TM} 10XM
  - Internal 3x3 water channel removed
  - Fuel rod diameter increased
  - ➡ Geometric moderator-to-fuel-ratio decreased: **2.5 → 1.5**



- Volumetric power density as in conventional core
  - ➡ Specific power density is decreased
- Average enrichment: 5 % Pu-fiss
- 4 enrichment levels to get flat power profile
- MOX-fuel with 65 % plutonium quality (UOX with 0.25 w/o U235)
  - Pu-Vector:

Pu238	Pu239	Pu240	Pu241	Pu242
2	56.5	26.1	8.6	6.8

Cross Section Generation

- Generation of 2group homogenized XS-library with SCALE6.1/TRITON

- User-defined Dancoff factors calculated with MCDancoff in SCALE6.1
  - depending on position
  - depending on coolant void content

- Transfer to PMAX-format with GenPMAXS interface

- Considering history of
  - coolant void content: 0 %, 40 %, 80 %
  - control rod position: in/out

Cross Section Branch Structure

Karlsruhe Institute of Technology

- 4 state variables:
  - Control rod position (CR)
  - Coolant density (DC)
  - Fuel temperature (TF)
  - Moderator temperature (TM)
- Core conditions for whole range from Cold-Zero-Power (CZP) to high-void Hot-Zero-Power (HZP) covered
- Advanced new-formatted branch data structure in TRITON used to modify bypass moderator properties independently from coolant in fuel channel for CZP branches
  - ✓ All branches at fresh conditions validated with separate calculations

	CR	DC, g/cm³	TF, K	TM, K
RE	out	0.4572	800.00	560.47
CR	in	0.4572	800.00	560.47
DC	out	0.1074	800.00	560.47
DC	out	0.1773	800.00	560.47
DC	out	0.2473	800.00	560.47
DC	out	0.7370	800.00	560.47
DC	out	0.9982	800.00	560.47
DC	in	0.1074	800.00	560.47
DC	in	0.1773	800.00	560.47
DC	in	0.2473	800.00	560.47
DC	in	0.7370	800.00	560.47
DC	in	0.9982	800.00	560.47
TF	out	0.1773	560.47	560.47
TF	out	0.1773	1100.00	560.47
TF	out	0.4572	560.47	560.47
TF	out	0.4572	1100.00	560.47
TF	out	0.7370	560.47	560.47
TF	out	0.7370	1100.00	560.47
TF	out	0.9982	293.00	560.47
TF	in	0.9982	293.00	560.47
TC	out	0.9982	293.00	293.00
TC	in	0.9982	293.00	293.00

Core Model – Plant data

German Gen-II BWR type 72		
Rated thermal core power	3840	MW
Average power density	57	W/cm³
Number of fuel assemblies	784	
Rated active core flow	11802.4	kg/s
Estimated bypass fraction	17.5 %	
Inlet enthalpy	1222	kJ/kg
Inlet subcooling	52	kJ/kg

Core Model – Mapping of Quarter Core

- Used new assy_type input
  - + Easy and intiutive input

Radial mapping

0	empty position
1	FA Type 1, TH-Type 1
1	FA Type 1, TH-Type 2
2	Reflector assembly

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2
3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2
4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2
5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2
6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2
7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2
8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2
9	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	0
10	1	1	1	1	1	1	1	1	1	1	1	1	1	2	0	0
11	1	1	1	1	1	1	1	1	1	1	1	1	1	2	0	0
12	1	1	1	1	1	1	1	1	1	1	1	1	2	2	0	0
13	1	1	1	1	1	1	1	1	1	1	1	2	2	0	0	0
14	1	1	1	1	1	1	1	1	2	2	2	2	0	0	0	0
15	1	1	1	1	1	1	1	2	2	0	0	0	0	0	0	0
16	2	2	2	2	2	2	2	2	0	0	0	0	0	0	0	0

- 1 Fuel type
- 2 thermal-hydraulic channel types with different inlet orifice loss coefficient
- Local loss coefficients for:
  - Upper tie plate (UTP)
  - Grid spacer
  - Lower tie plate (LTP)
  - Inlet orifice

Axial mapping

1	Fuel node
2	Radial Reflector node
3	Bottom Reflector node
4	Top Reflector node

	FA		Refl.
27	4	4	4
26	1	1	2
25	1	1	2
24	1	1	2
23	1	1	2
22	1	1	2
21	1	1	2
20	1	1	2
19	1	1	2
18	1	1	2
17	1	1	2
16	1	1	2
15	1	1	2
14	1	1	2
13	1	1	2
12	1	1	2
11	1	1	2
10	1	1	2
9	1	1	2
8	1	1	2
7	1	1	2
6	1	1	2
5	1	1	2
4	1	1	2
3	1	1	2
2	3	3	3
1	3	3	3

K_{UTP}

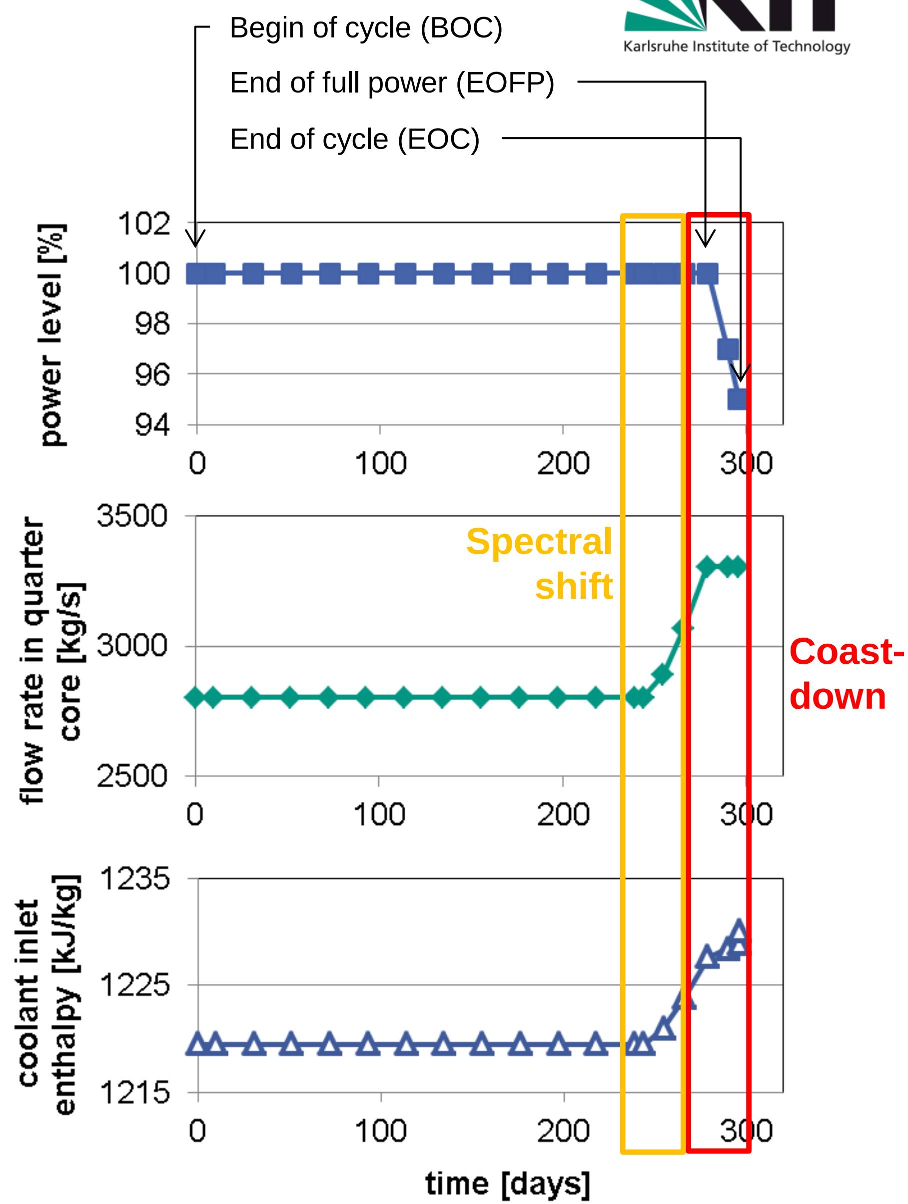
K_{grid}

K_{LTP}

$K_{orifice,1} < K_{orifice,2}$

General Cycle Definition

- Cycle length of 300 days
- 6 batches with 132 FA per batch
- Control of excess reactivity with control rods
- Short spectral shift & coastdown

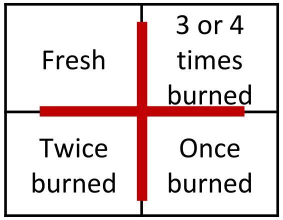


Reloading & Shuffling Pattern

- Requirements:
  - Flat power profile
  - Long cycle length and high discharge burnup
  - Low leakage
  - Adequate safety parameters

- Best practice guideline:
  - Fresh FA not next to another fresh or once-burned FA
  - Fresh FA not next to inserted CR if possible
  - Core cell of 4 FA surrounding a CR consist of
    - 1 fresh and 1 once-burned FA diagonal to each other
    - 2 individual older FA of batches 3-5
  - FA of batch 6 moved to core periphery -> low leakage
  - Individually exchange FA of older batches to obtain flat power profile

Core cell:



Control Rod Withdrawel Pattern in Cycle

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1	0	0	2	2	0	0	4	4	0	0	8	8	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	2	0	0	3	3	0	0	5	5	0	0	10	10	0	0	0
5	2	0	0	3	3	0	0	5	5	0	0	10	10	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	4	0	0	6	6	0	0	7	7	0	0	12	12	0	0	0
9	4	0	0	6	6	0	0	7	7	0	0	12	12	0	0	
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
12	8	0	0	11	11	0	0	9	9	0	0	0	0	0		
13	8	0	0	11	11	0	0	9	9	0	0	0	0			
14	0	0	0	0	0	0	0	0	0	0	0	0				
15	0	0	0	0	0	0	0	0	0							
16	0	0	0	0	0	0	0	0								

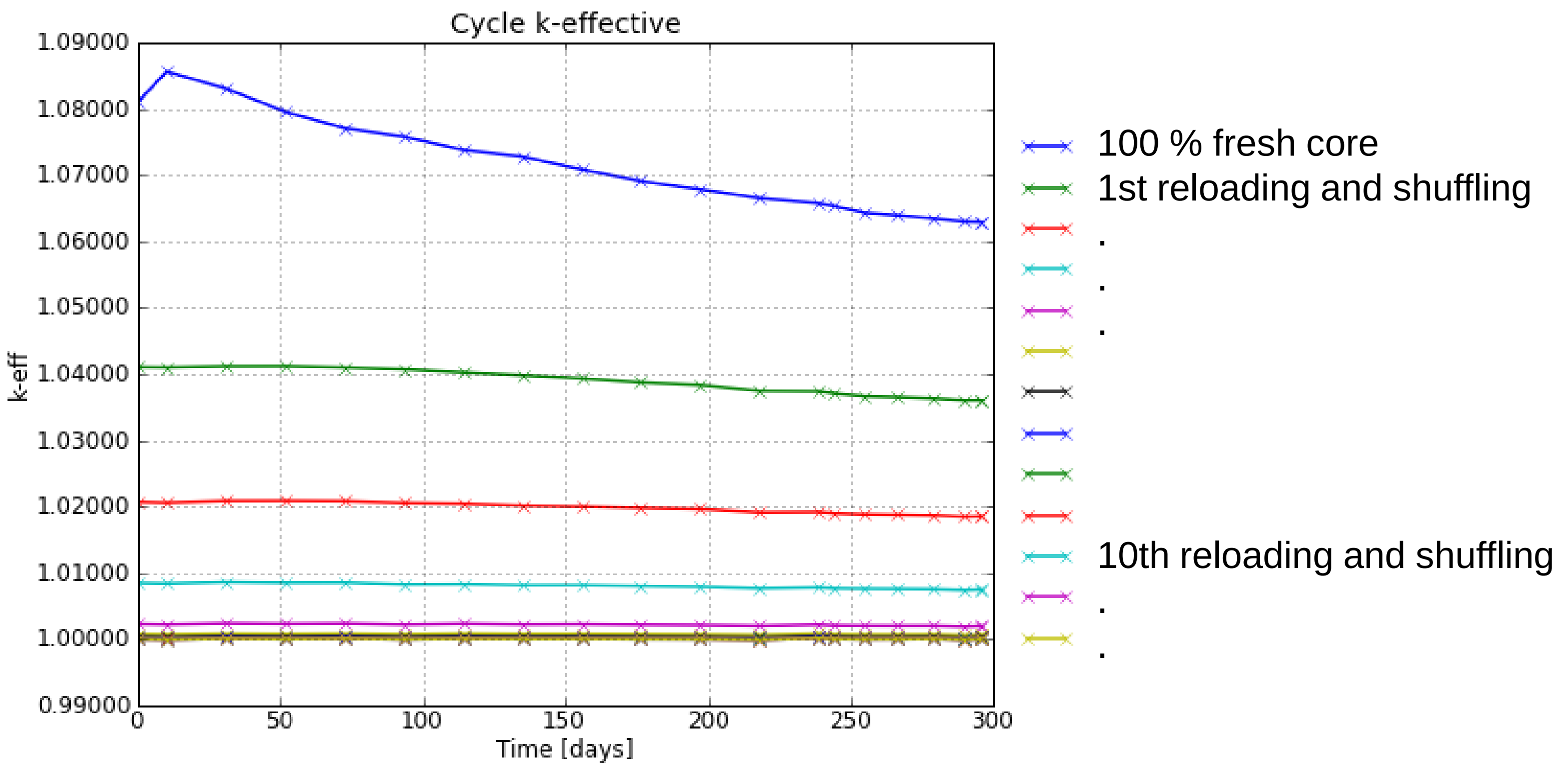
BANK		2	3	4	5	6	7	10
BANK_DEF	1	0	0	0	0	0	0	57
BANK_DEF	2	0	0	0	0	0	0	65
BANK_DEF	3	0	0	0	37	0	0	100
BANK_DEF	4	0	0	0	85	0	0	100
BANK_DEF	5	0	0	0	100	31	0	100
BANK_DEF	6	0	0	0	100	58	0	100
BANK_DEF	7	26	0	0	100	100	0	100
BANK_DEF	8	58	0	0	100	100	0	100
BANK_DEF	9	100	0	0	100	100	32	100
BANK_DEF	10	100	14	0	100	100	100	100
BANK_DEF	11	100	36	0	100	100	100	100
BANK_DEF	12	100	100	15	100	100	100	100
BANK_DEF	13	100	100	40	100	100	100	100
BANK_DEF	14	100	100	50	100	100	100	100
BANK_DEF	15	100	100	100	100	100	100	100
BANK_DEF	16	100	100	100	100	100	100	100
BANK_DEF	17	100	100	100	100	100	100	100
BANK_DEF	18	100	100	100	100	100	100	100
BANK_DEF	19	100	100	100	100	100	100	100
BANK_DEF	20	100	100	100	100	100	100	100

coast down

- **Manual** adjustment of steps
- All uncolored control rod banks withdrawn
- CR-density could be reduced with burnable absorbers

RESULTS

Convergence of Multi-Cycle-Depletion Analysis



- Equilibrium cycle reached in 10-15 iterations depending on convergence criterion (e.g. local change in burnup < 0.1 MWd/kgHM)

Power Distribution

BOC

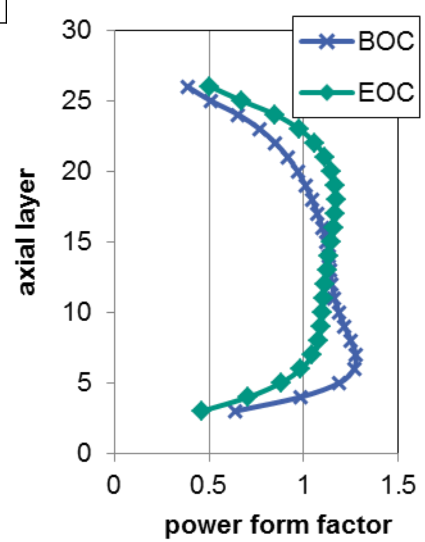
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1.3	1.3	1.3	0.9	0.9	1.2	1.3	0.9	0.9	1.2	1.2	1.3	1.1	0.8	0.5
2	1.3	1.4	1.2	1.3	1.2	1.4	1.2	1.3	1.2	1.4	1.3	1.3	1	0.8	0.5
3	1.3	1.3	1.3	1.2	1.3	1.2	1.3	1.3	1.3	1.2	1.3	1.2	1.1	0.8	0.5
4	0.9	1.3	1.2	1	0.9	1.3	1.2	1	0.9	1.3	1.2	1.1	0.9	0.8	0.5
5	1	1.2	1.3	0.9	0.9	1.2	1.3	0.9	1	1.2	1.2	1	0.9	0.7	0.4
6	1.2	1.4	1.2	1.3	1.2	1.3	1.2	1.3	1.2	1.3	1.1	1.2	0.8	0.6	0.4
7	1.2	1.2	1.3	1.2	1.3	1.2	1.2	1.1	1.2	1.2	1.2	1.1	0.8	0.5	0.3
8	0.9	1.3	1.2	1	0.9	1.3	1.1	0.9	0.8	1.2	1.1	0.9	0.6	0.4	
9	0.9	1.2	1.3	0.9	0.9	1.1	1.1	0.8	0.8	1	1	0.8	0.5		
10	1.2	1.4	1.2	1.3	1.2	1.3	1.1	1.2	1	1	0.8	0.6	0.4		
11	1.3	1.3	1.3	1.2	1.2	1.1	1.2	1.1	1	0.8	0.6	0.4	0.3		
12	1.2	1.3	1.2	1.3	1.2	1.2	1.1	0.9	0.8	0.6	0.4	0.3			
13	1.1	1	1.1	1	1	0.9	0.8	0.6	0.5	0.4	0.3				
14	0.7	0.8	0.8	0.8	0.7	0.6	0.5	0.4							
15	0.5	0.5	0.5	0.4	0.4	0.4	0.3								

Maximum Pos. Maximum Value
(2, 2) 1.4107

EOC

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1.2	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.2	1.2	1.1	1.1	0.9	0.7	0.4
2	1.3	1.4	1.2	1.4	1.3	1.4	1.3	1.4	1.3	1.3	1.2	1.1	0.9	0.7	0.4
3	1.3	1.3	1.3	1.3	1.3	1.3	1.4	1.3	1.3	1.2	1.2	1.1	0.9	0.7	0.4
4	1.3	1.4	1.3	1.3	1.3	1.4	1.3	1.3	1.2	1.3	1.1	1.1	0.9	0.7	0.4
5	1.4	1.3	1.4	1.3	1.3	1.3	1.3	1.2	1.3	1.2	1.2	1	0.9	0.6	0.4
6	1.3	1.4	1.3	1.4	1.3	1.4	1.3	1.3	1.2	1.2	1.1	1	0.8	0.5	0.3
7	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.2	1.2	1.1	1.1	0.9	0.7	0.4	0.3
8	1.2	1.4	1.3	1.3	1.2	1.3	1.2	1.2	1.1	1.1	1	0.8	0.5	0.4	
9	1.2	1.2	1.3	1.2	1.2	1.2	1.2	1.1	1	1	0.9	0.7	0.5		
10	1.2	1.3	1.2	1.3	1.2	1.2	1.1	1.1	1	1	0.8	0.5	0.3		
11	1.2	1.2	1.2	1.1	1.1	1	1.1	1	0.9	0.8	0.6	0.4	0.3		
12	1	1.1	1.1	1.1	1	1	0.9	0.8	0.7	0.5	0.4	0.3			
13	0.9	0.9	0.9	0.9	0.9	0.7	0.7	0.5	0.4	0.3	0.3				
14	0.6	0.7	0.6	0.6	0.6	0.5	0.4	0.4							
15	0.4	0.4	0.4	0.4	0.3	0.3	0.3								

Maximum Pos. Maximum Value
(2, 6) 1.4032



Burnup Distribution

BOC

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	19	19	7.7	21	13	18	7.5	16	22	15	24	6.6	7.4	27	30
2	19	0	24	0	14	0	26	0	13	0	15	0	25	14	31
3	7	22	6.9	18	7.7	22	7.2	15	5.8	22	6.7	13	6.7	20	32
4	25	0	21	13	19	0	15	0	22	0	28	0	13	14	32
5	7.7	14	7	18	12	25	6.5	22	7.2	14	6.8	13	7.5	15	32
6	13	0	22	0	25	0	18	0	19	0	26	0	26	28	31
7	15	25	7	14	6.4	18	7.3	26	7.3	19	0	6	21	29	32
8	20	0	21	0	24	0	25	7.6	18	0	12	14	29	31	
9	14	22	5.7	20	7.5	18	6.3	19	16	24	0	18	31		
10	19	0	26	0	15	0	18	0	25	0	12	29	32		
11	5.6	14	6.4	28	6.7	26	0	12	0	12	28	29	32		
12	26	0	13	0	13	0	6.2	21	18	28	29	31			
13	7.3	26	6.7	13	7.8	25	21	31	32	30	31				
14	28	14	25	14	25	30	29	30							
15	30	32	31	33	31	32	31								

EOC

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	26	26	15	28	19	25	15	22	27	21	30	13	13	31	32
2	26	7.8	31	7.7	22	7.7	33	7.3	20	7.2	21	6.7	31	18	33
3	15	29	14	25	15	29	15	22	13	29	14	19	12	24	34
4	32	7.7	28	19	25	7.5	22	6.7	28	7.3	35	6.6	19	18	34
5	15	21	14	24	18	32	14	28	14	21	14	19	13	18	35
6	20	7.6	29	7.4	31	7.5	25	7.5	26	7.3	32	6.2	30	31	33
7	22	32	14	21	14	25	15	32	14	26	6.7	12	26	31	34
8	25	7	28	6.3	30	7.2	32	14	24	6.8	18	18	32	33	
9	19	29	13	26	14	25	13	25	22	30	5.7	22	34		
10	25	7	32	7	21	6.9	24	6.7	31	5.8	16	33	34		
11	12	20	13	34	13	32	6.4	18	5.6	16	31	32	33		
12	32	6.5	19	6.4	19	6	12	26	22	31	31	33			
13	13	31	12	18	13	30	25	34	34	32	33				
14	32	18	29	18	28	33	32	32							
15	33	34	34	35	33	34	33								

- Discharge burnup is quite low, because of reduced power density
- Core power has to be maintained
- To increase burnup
  - reduction of core height is required
  - Enrichment has to be increased
  - Larger number of fuel rods per FA needed to keep low linear heat rates

Reactivity Coefficients

- Point kinetics data obtained by PARCS and written to .pkd file

	DC($/kgm^{-3})	TF ($/K)	DVoid ($/%Void)
BOC	2.60E-02	-5.96E-03	-1.81E-01
EOFP	2.60E-02	-3.71E-03	-1.82E-01
EOC	2.55E-02	-4.72E-03	-1.78E-01

Dvoid = -0.00698*DC

1pcm = 1$*1e5*$\beta_{eff}$
(β_{eff} from .pkd file)

	DC(pcm/kgm^{-3})	TF (pcm/K)	DVoid (pcm/%Void)
BOC	10.3	-2.4	-71.6
EOFP	10.5	-1.5	-73.1
EOC	10.3	-1.9	-71.6

- DVoid obtained from DC with coolant properties at average core pressure of 72 bars (core average void not printed in PARCS)

- $$\frac{DC}{Dvoid} = \frac{\rho_{C,100\%Void} - \rho_{C,0\%Void}}{100\% - 0\%} = \frac{(37.9 - 735.5)^{kg}/_{m^3}}{100\%} = -0.00698$$

⇨ Reactivity coefficients for core design are adequate

Shutdown Margin

- SDM with stuck rod is requested to be larger than -1.5%
- Only Rod-Banks with 4 control rods in quarter core model
- All-Rods-In (ARI) investigated for core design

	ARI Cold SDM	ARI Hot SDM
BOC	-3.03%	-3.10%
EOFP	-5.46%	-5.50%
EOC	-5.61%	-5.64%

⇨ Shutdown Margin has to be investigated in more detail, but seems to be sufficient

⇨ Algorithm to search for most reactive rod would save a lot of work

Summary

- Equilibrium cycle for low moderated BWR core was investigated with PARCS/PATHS
- Reactivity coefficients and ARI shutdown margin are adequate

Outlook

- Development of full core model to
  - determine shutdown margin with single most reactive rod
  - account for rotational symmetry
- Investigation with cross-sections with more energy-groups
- Design changes to increase discharge burnup
- Use pin power reconstruction to get local pinwise power distribution for external investigation of local safety parameters with INR in-house sub-channel code SUBCHANFLOW

Thank you for your attention!

Contact:

Karlsruhe Institute of Technology (KIT) – Campus Nord
Institute for Neutron Physics and Reactor Technology (INR)
Reactor Physics and Dynamics Group (RPD)

Dipl.-Ing. Markus T. Schlenker

Hermann-von-Helmholtz-Platz 1
76344 Eggenstein-Leopoldshafen, Germany

Phone: +49 721 608 2 2544
Fax: +49 721 608 2 3718
Email: markus.schlenker@kit.edu