Increasing the Fuel Utilization in Gen-II BWR with Reduced-Moderation Square Lattice Fuel Assemblies

ICAPP2014-14145

Institute for Neutron Physics and Reactor Technology

Markus Schlenker & **Victor Sanchez-Espinoza**

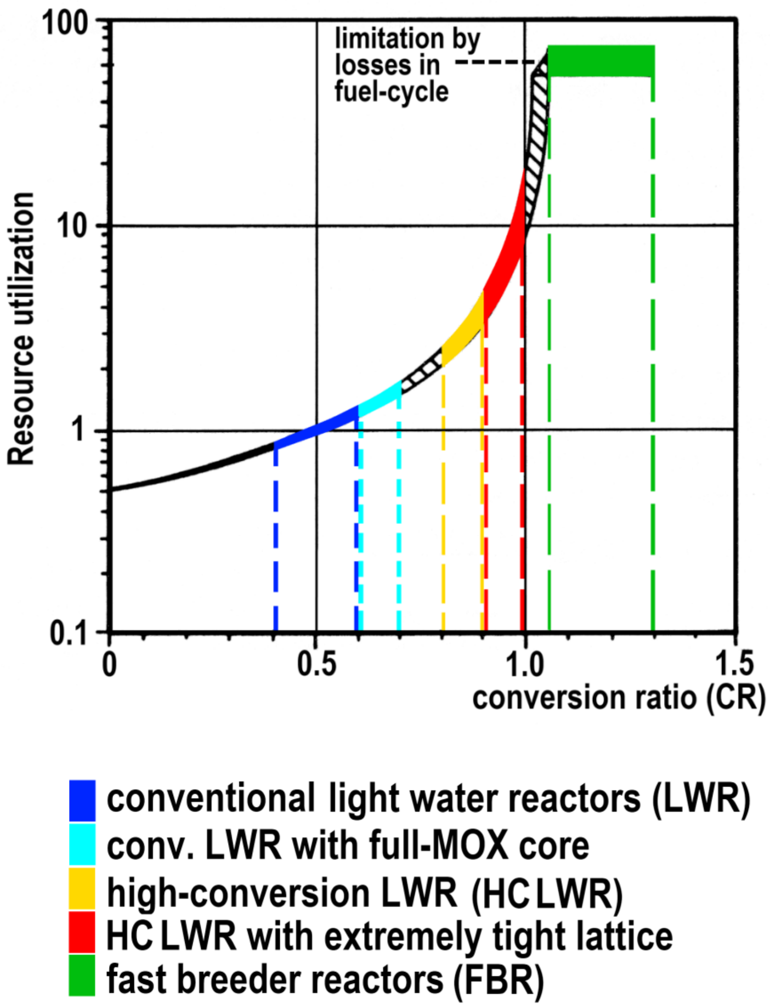
Karlsruhe Institute of Technology,
Institute for Neutron Physics and Reactor Technology

2014 International Congress on Advances in Nuclear Power Plants (ICAPP)

Westin
Charlotte, North Carolina, U.S.A.
April 6-9, 2014

Motivation

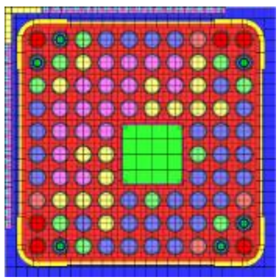
- Improve fuel utilization in light water reactors (LWR) by increasing the conversion ratio
- Make multi-recycling more feasible
- Use advantages of boiling water reactor (BWR)
- Maintain inherent safe behavior
- Use proven plant design (Gen-II BWR: German KWU series 72)



Solution approach

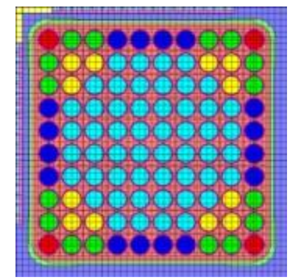
Fuel assembly (FA) based analysis with lattice physics code:

ATRIUM™ 10XM (reference) → **Low moderated FA**



Reduce Moderation:
- Remove water structures
- Modify fuel pin radius
- Modify pitch

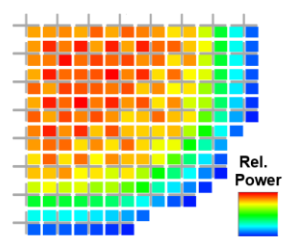
Keep FA-pitch, FA-channel, control rod geometry



Iterations

Validation with Monte Carlo code:
- Confirm deterministic solution for harder neutron spectrum
- Confirm void reactivity coefficient

3-D core analysis (not in this paper):
- Assess global safety behavior
- Obtain average T-H conditions for more representative depletion analysis (FA level)



SCALE6.1 code package

- TRITON lattice physics sequence:
  - ENDF/B-VII multigroup cross-sections in 238 energy groups
  - BONAMI/CENTRM/PMC for multi-group cross-section processing
  - Manual definition of Dancoff factors
  - NEWT deterministic 2-D S_N code
  - Flexible mesh
  - ORIGEN-S depletion code

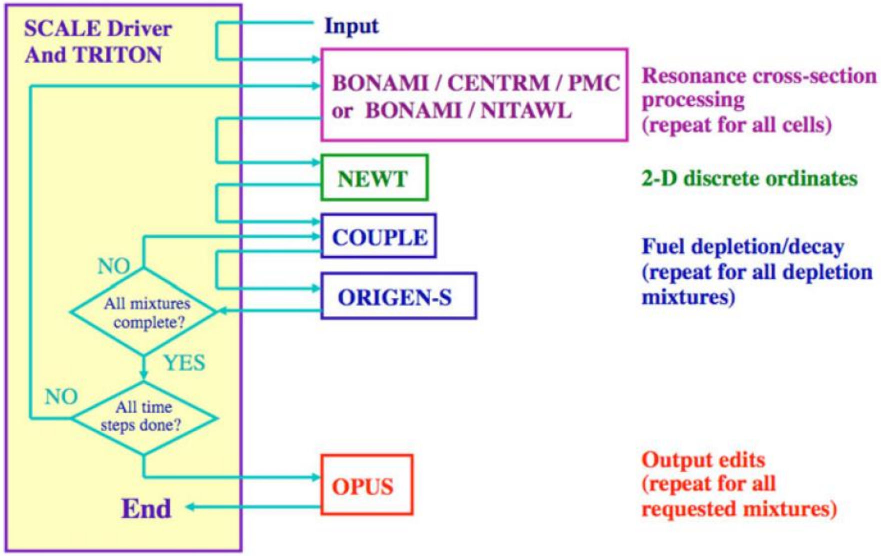


Fig. 1. Flowchart for TRITON/NEWT depletion sequence.

M. D. DeHart, S. M. Bowman 2010, *Reactor Physics Methods and Analysis Capabilities in Scale*, Nuclear Technology, Vol. 174, May 2011

- KENO-VI Monte Carlo code
  - ENDF/B-VII cross-sections
    - continuous energy
    - multigroup (238 energy groups)
  - BONAMI/CENTRM/PMC for multigroup cross-section processing

Parametric design studies (TRITON / NEWT)

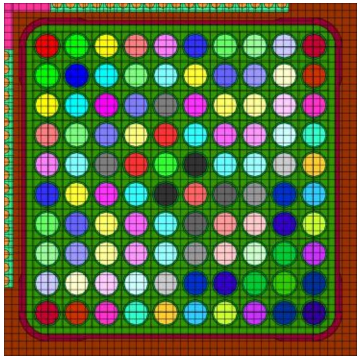
Parametrization:

Case	1	2	3	4	5	6	7	Ref
Lattice dimension	10x10	10x10	10x10	12x12	10x10	10x10	10x10	10x10-9
Pitch, cm	1.290	1.285	1.285	1.070	1.285	1.285	1.285	-
R_{rod}, cm	0.545	0.573	0.573	0.465	0.573	0.573	0.573	0.514
R_{fuel}, cm	0.470	0.494	0.494	0.401	0.494	0.494	0.494	0.452
Rod distance, cm	0.20	0.14*	0.14	0.14	0.14	0.14	0.14	-
moderator to fuel ratio (MFR)	1.842	1.543	1.543	1.695	1.543	1.543	1.543	2.477
Fuel volume*, cm^3/cm	69.5	76.7	76.7	72.8	76.7	76.7	76.7	58.4
Av. enrichm., wt-%	5	5	6	5	5	5	6	4.4
Pu-Vector (see below)	1	1	1	1	2	3	3	1

*Minimum rod clearance in study

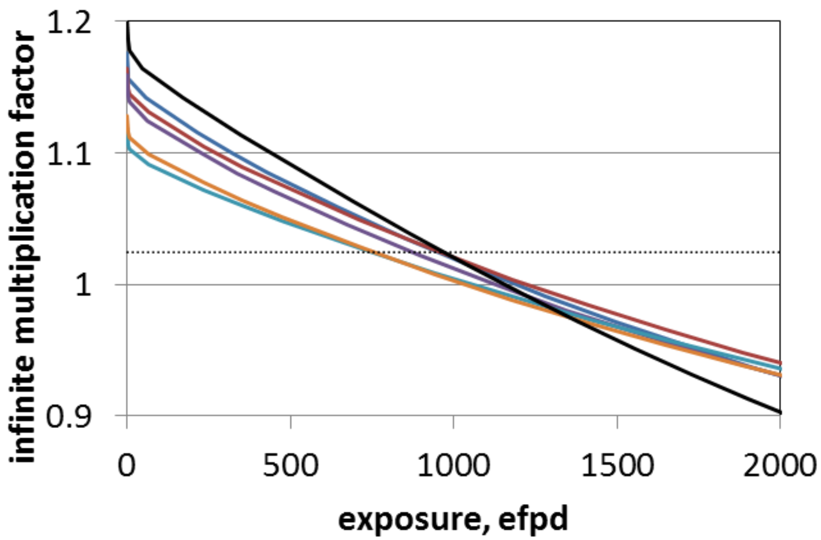
Fuel material compositions:

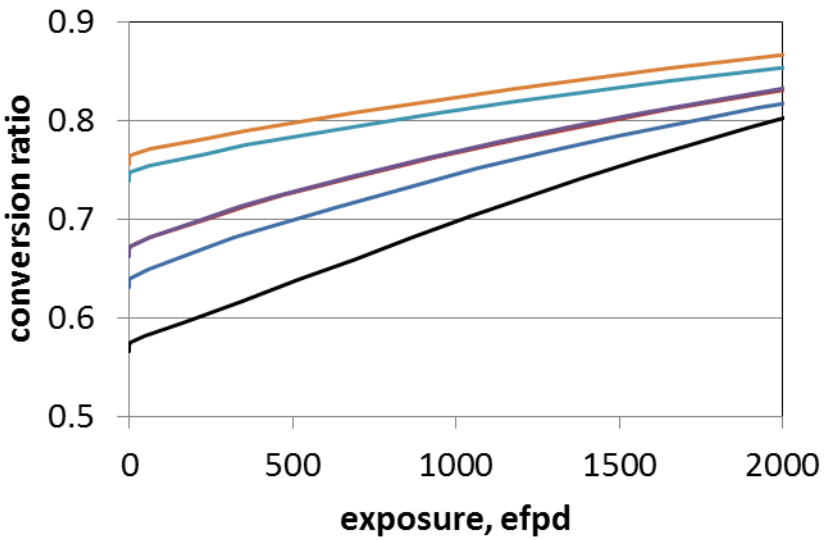
Pu-Vector	Pu238	Pu239	Pu240	Pu241	Pu242	Pu_{fiss}
1	2	56.5	26.1	8.6	6.8	65.1
2	4	48	31	7	10	55
3	4	38	33	12	13	50



Results for k_{eff} and CR (5% Pu_{fiss})

Case	1	2		4	5	6		Ref
Lattice dimension	10x10	10x10		12x12	10x10	10x10		10x10-9
R_{rod}, cm	0.545	0.573		0.465	0.573	0.573		0.514
moderator to fuel ratio (MFR)	1.842	1.543	1.543	1.695	1.543	1.543	1.543	2.477
Pu-Vector (see below)	1	1		1	2	3		1

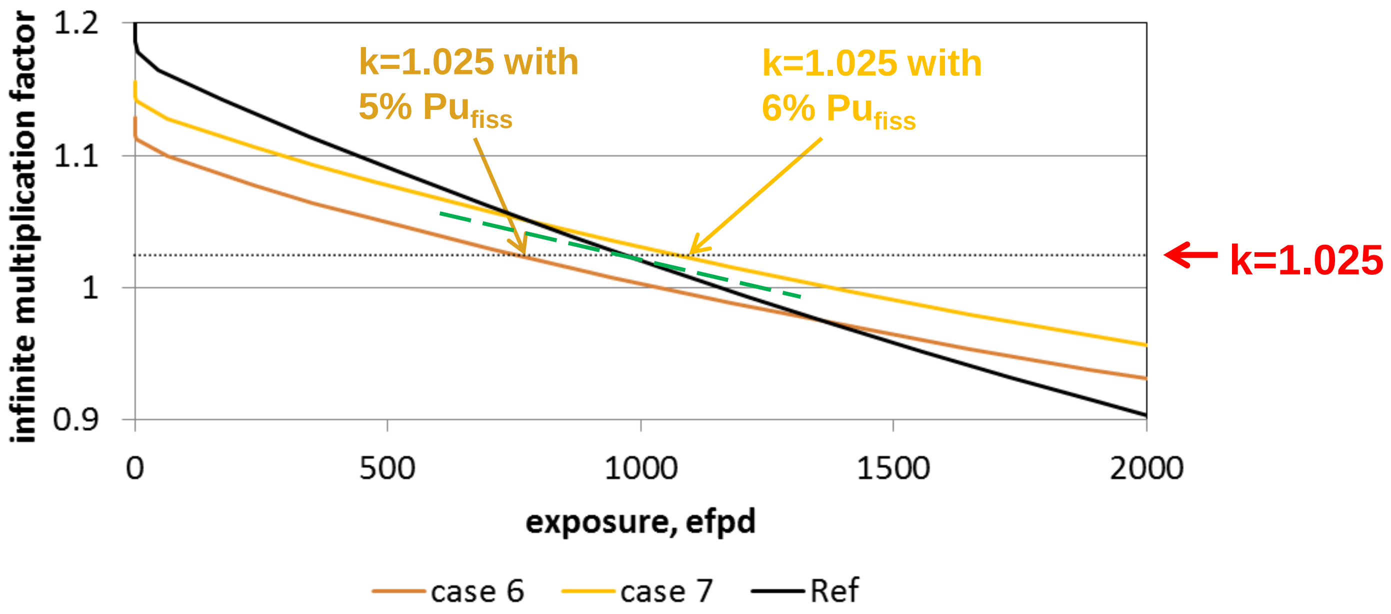




- K_{eff} decrease slower due to higher CR
- Results not directly comparable due to differing achievable cycle length

Interpolating results to compare cases

- Apply linear reactivity model (Driscoll, 1990)
- Assume leakage of ~2.5 % in effective system
- Matching cycle length for matching k_{inf} at k=1.025
- Example:



- Interpolation suggest ~5.6% Pu_{fiss} for comparable cycle length

Results – Fuel utilization

- Parametrization with adjusted enrichment for comparable cycle length

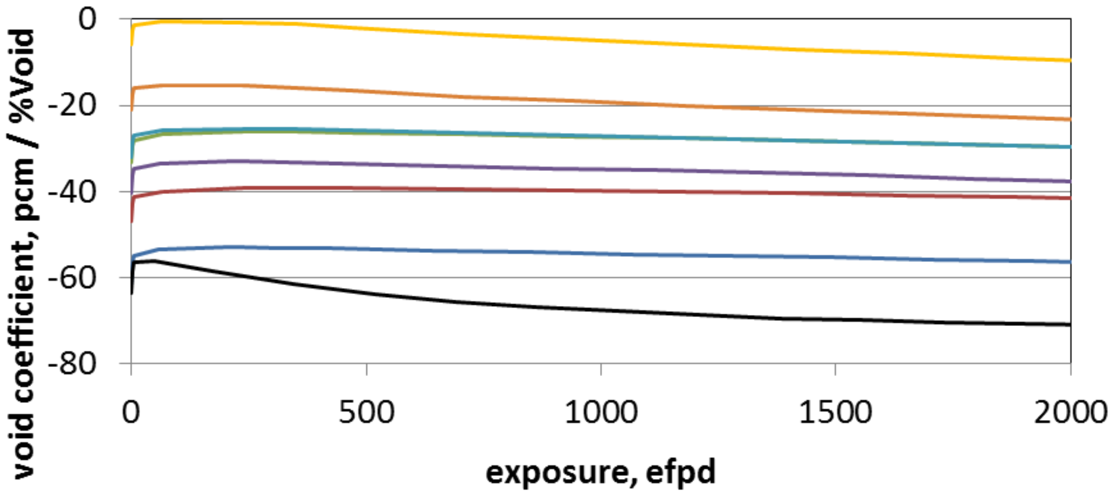
Case	1	2		4*	5*	6*		Ref
Lattice dimension	10x10	10x10		12x12	10x10	10x10		10x10-9
Pitch, cm	1.290	1.285		1.070	1.285	1.285		-
R_{rod}, cm	0.545	0.573		0.465	0.573	0.573		0.514
Rod distance, cm	0.20	0.14		0.14	0.14	0.14		-
MFR	**1.842**	**1.543**		**1.695**	**1.543**	**1.543**		**2.477**
Av. enrichm., wt-%	5	5		5.3	5.6	5.6		4.4
Fresh Pu_{qual}	**0.65**	**0.65**		**0.65**	**0.55**	**0.50**		**0.65**

Cycle length, efpd	**270**	**271**		**273**	**265**	**265**		**276**
Cycle average CR	**0.729**	**0.753**		**0.744**	**0.780**	**0.794**		**0.68**
Pu-quality-change (discharge - fresh)	**-0.08**	**-0.06**		**-0.06**	**-0.03**	**-0.03**		**-0.16**

- Slightly better fuel utilization with thicker rods (smaller MFR!)
- Best fuel utilization with lowest fresh Pu-quality
- Degradation of Pu-vector significantly reduced

Results – Void reactivity coefficient

Case	1	2	3	4	5	6	7	Ref
Lattice dimension	10x10	10x10	10x10	12x12	10x10	10x10	10x10	10x10-9
moderator to fuel ratio (MFR)	1.842	1.543	1.543	1.695	1.543	1.543	1.543	2.477
Av. enrichm., wt-%	5	5	6	5	5	5	6	4.4
Pu-Vector	1	1	1	1	2	3	3	1

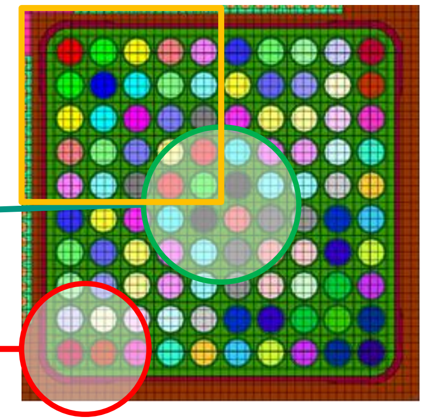


- VC reduced but negative

Case	1	2	3	4	5	6	7
Approximate limiting av. enr. for negative VC, wt-%	~8.7	~7.7		~7	~6.7	~6	

User-defined Dancoff factors (C)

- Only needed for multi-group calculations
- Standard-approach:
  - Infinite lattice C in every unit cell
- BWR:
  - Quasi infinitive lattice in center
    → infinite lattice C ok
  - Very heteregeneous peripheral lattice
    → infinite lattice C not correct!



- C is void dependent
- C can be grouped (center, side, corner)
- e.g. in upper left quadrant of low moderated FA:

0 % void content

0.23	0.33	0.34	0.33	0.34
0.34	0.48	0.48	0.49	0.48
0.34	0.48	0.48	0.49	0.49
0.34	0.48	0.48	0.48	0.48
0.34	0.48	0.49	0.49	0.49

40 % void content

0.27	0.40	0.41	0.40	0.41
0.40	0.58	0.59	0.60	0.59
0.41	0.59	0.59	0.60	0.60
0.41	0.59	0.59	0.59	0.59
0.41	0.59	0.60	0.60	0.60

80 % void content

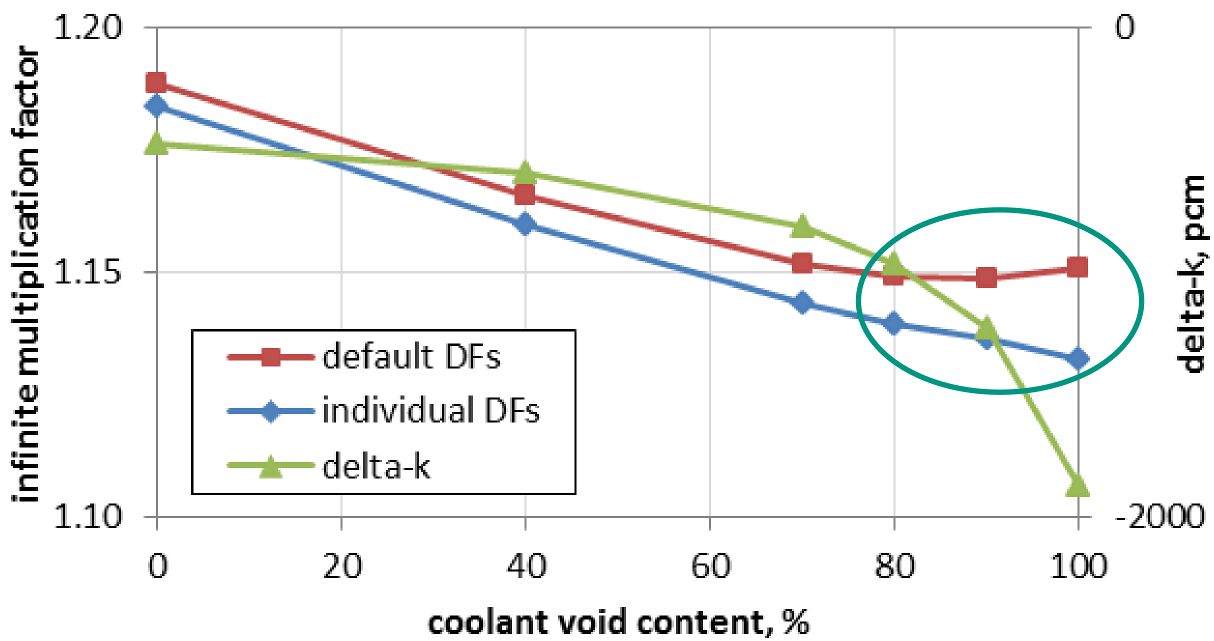
0.34	0.50	0.51	0.51	0.51
0.50	0.73	0.74	0.75	0.74
0.51	0.74	0.75	0.76	0.76
0.51	0.75	0.76	0.76	0.76
0.52	0.75	0.76	0.76	0.76

100 % void content

0.38	0.57	0.59	0.58	0.59
0.57	0.84	0.85	0.86	0.85
0.58	0.85	0.87	0.87	0.87
0.58	0.86	0.87	0.87	0.87
0.59	0.86	0.87	0.87	0.87

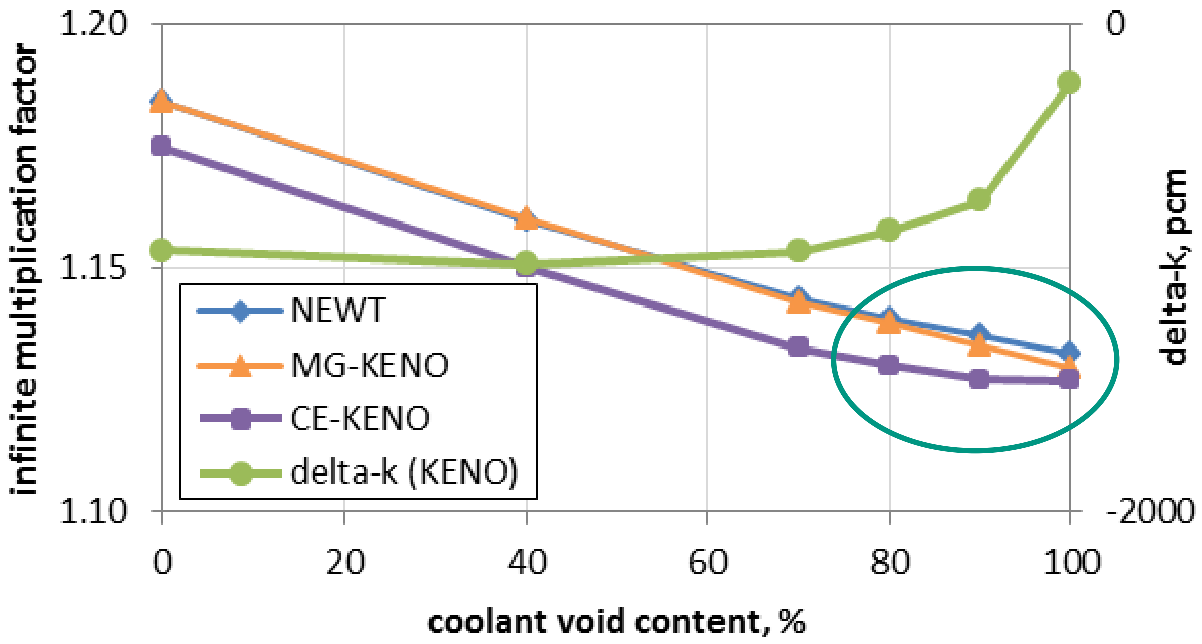
Karlsruhe Institute of Technology

Influence of C on results (NEWT)



- Overprediction by several 100 pcm without correct Dancoff factors
- Difference increases with void content
- Especially high disagreement for high void content

Validation studies (NEWT vs. KENO-VI)



- Good agreement of NEWT and MG-KENO
- Difference of <1% between MG-KENO and CE-KENO
- Bad agreement for void > 80%
- Potential sources for differences between MG-KENO and CE-KENO :
  - S(α,β) treatment in CE-KENO, Dancoff factors, Multi-group approximations

Reference to KENO validation*

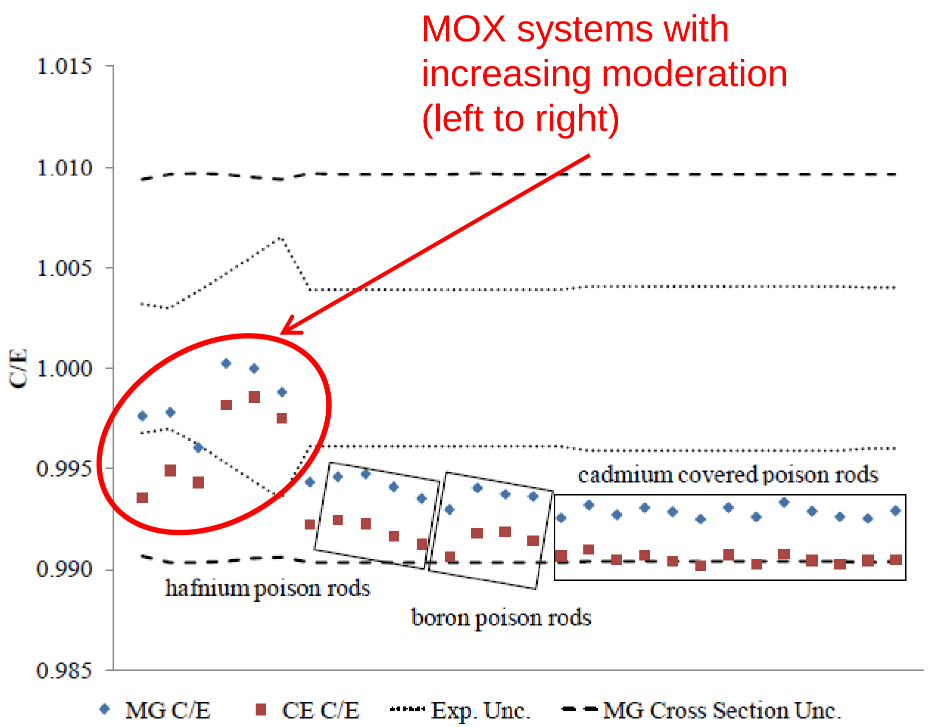


Fig. 33. Detailed results for MCT systems, KENO-VI.*

- „…the differences between the **multigroup** and **continuous energy** results are expected to be minimized with a **pending S(α,β) update** for the **continuous energy** cross sections that will be available with a subsequent release of Scale."* (Scale6.2)

*W. J. Marshall, B. T. Rearden 2011, *Criticality Safety Validation of Scale 6.1*, ORNL/TM-2011/450

- Considering of all approximations and KENO validation shows, 1% difference between MG-KENO and CE-KENO is reasonable
- Prediction improvement with SCALE6.2 assessed in the future

Conclusions

Karlsruhe Institute of Technology

- Design studies for low moderated FA:
  - Improvement of the conversion ratio: 0.68 → 0.73 to 0.79
  - Slower degradation of plutonium quality: -0.16 → -0.03 to -0.08
→ Second recycling more feasible
  - Reduced but negative void reactivity coefficient
- Corrected Dancoff factors improve result significantly
- Validation of NEWT model with KENO shows reasonable agreement
- Potential sources for differences between MG-KENO and CE-KENO:
  - S(α,β) treatment in CE-KENO
  - Dancoff factors
  - Multi-group approximations
- High void content predictions disagree (KENO vs NEWT) and have to be investigated in the future

- Core calculations are needed for more representative BWR conditions

Acknowledgements

- The authors gratefully acknowledge the technical advice of Prof. H.-D. Berger, Dr. M. Rost and all other involved colleagues of AREVA GmbH and want to thank for the financial support of AREVA GmbH for this work.
- This work is also supported by the Reactor Safety Research Program of the Karlsruhe Institute of Technology (KIT).