

Preventing xenon oscillations in Monte Carlo burnup calculations by forcing equilibrium

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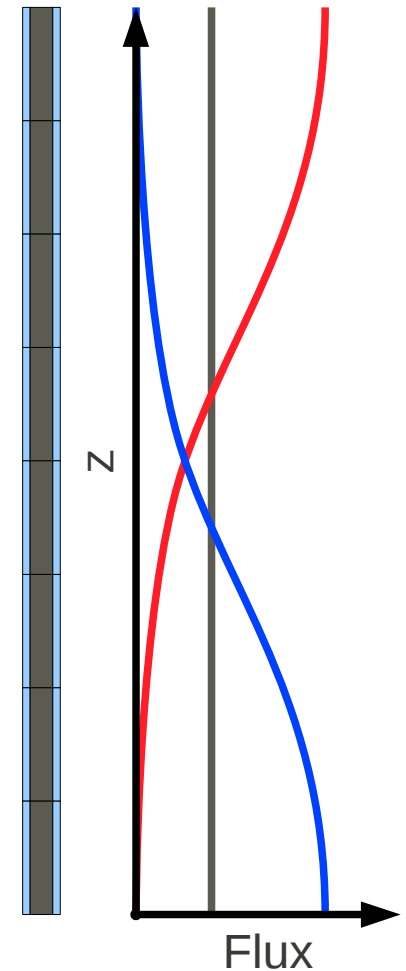
a) Aalto University, Finland

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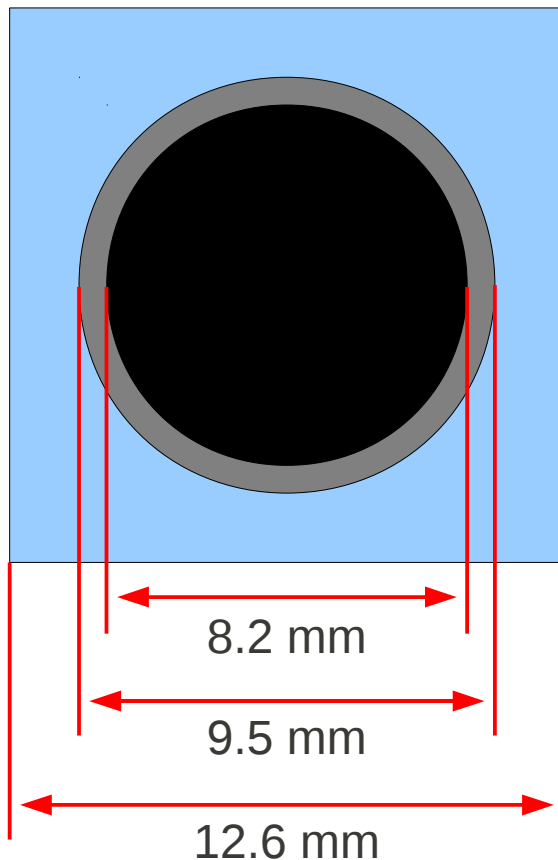
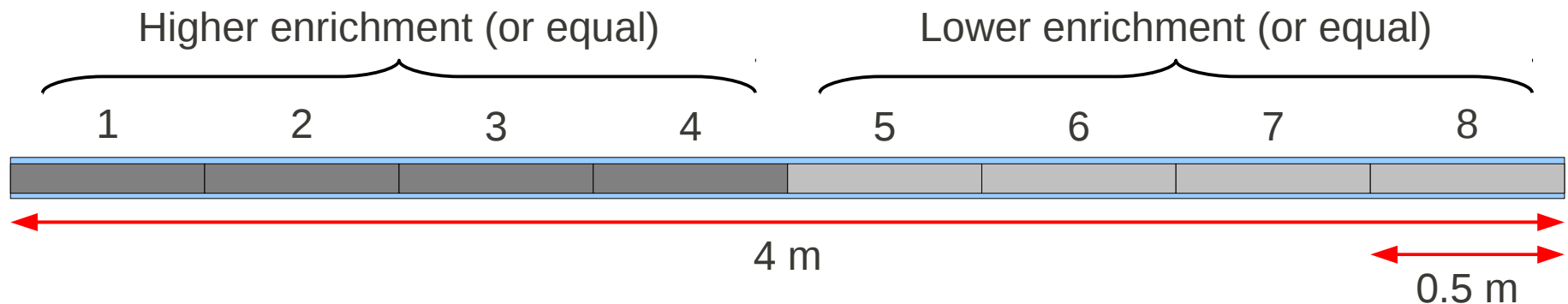
c) Royal Institute of Technology, Sweden

Xenon oscillations

- Physical xenon oscillations
 - Result from the delayed production of Xe-135
- Numerical xenon oscillations
 - Result from time discretization and the resulting delay in feedback from Xe-135 concentration
- Traditional geometries
 - Geometry dimensions \sim Migration length
 - Spatial oscillations impossible
- Large geometries (+ detailed discretization)
 - Dimensions \gg Migration-length
 - Prior studies: All old methods appear to suffer from numerical xenon oscillations [1,2]



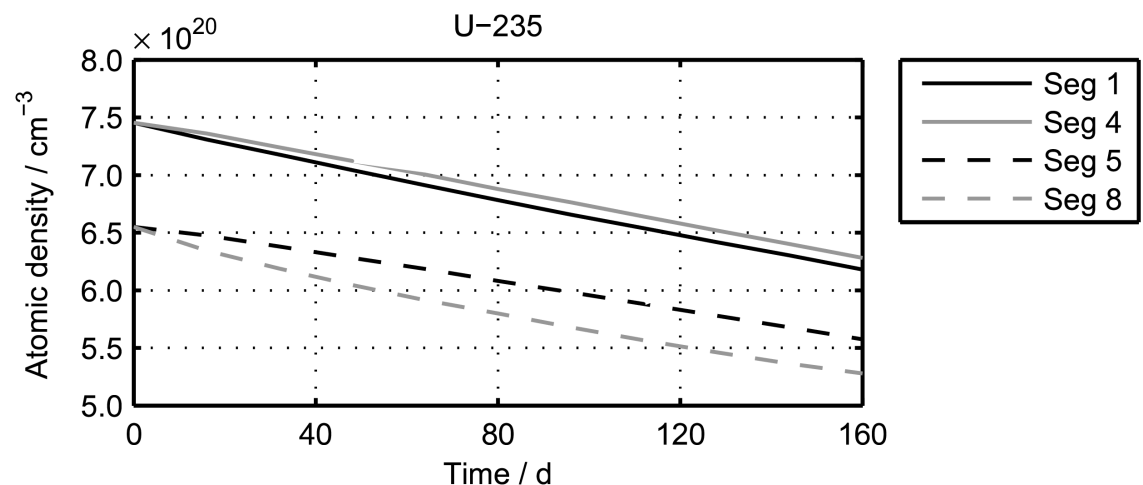
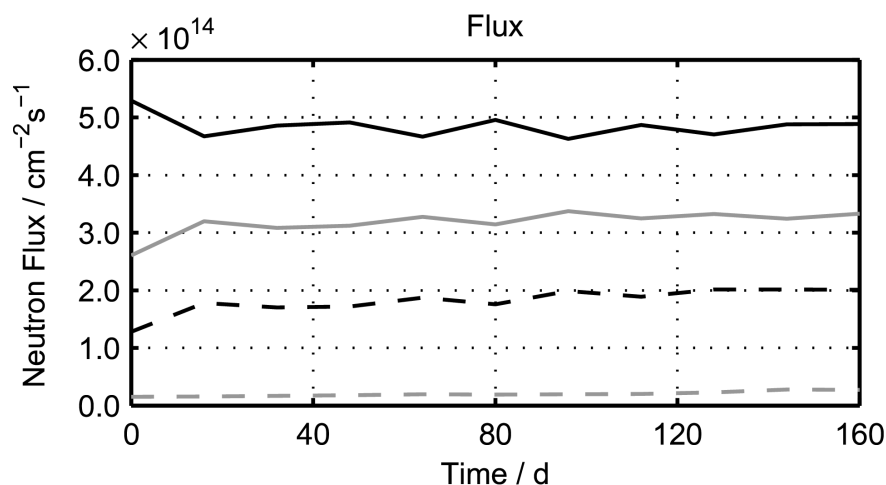
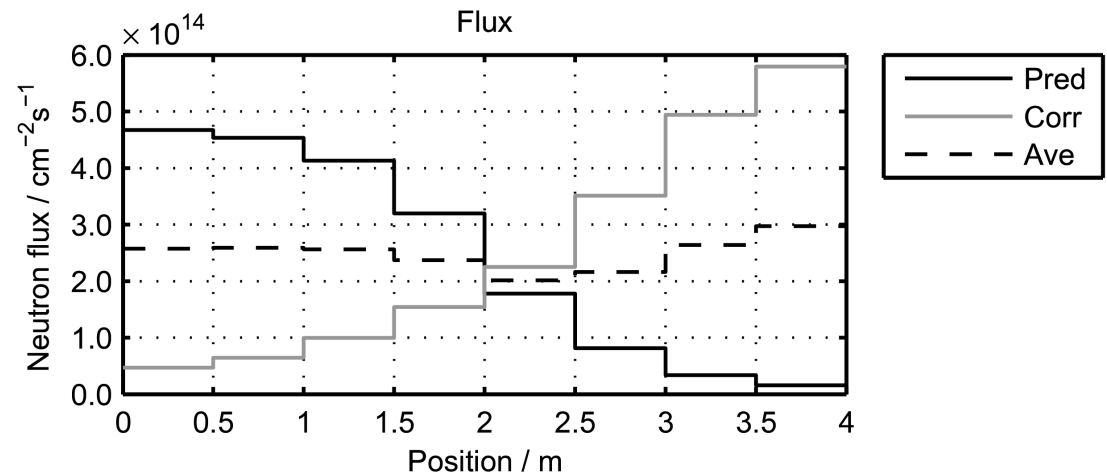
Test case



- 4 m PWR pin cell
- 8 axial segments
- Reflective boundary conditions
- Average enrichment 3.1 %
 - Enrichment increased in one end, reduced in the other
 - Average enrichment not changed

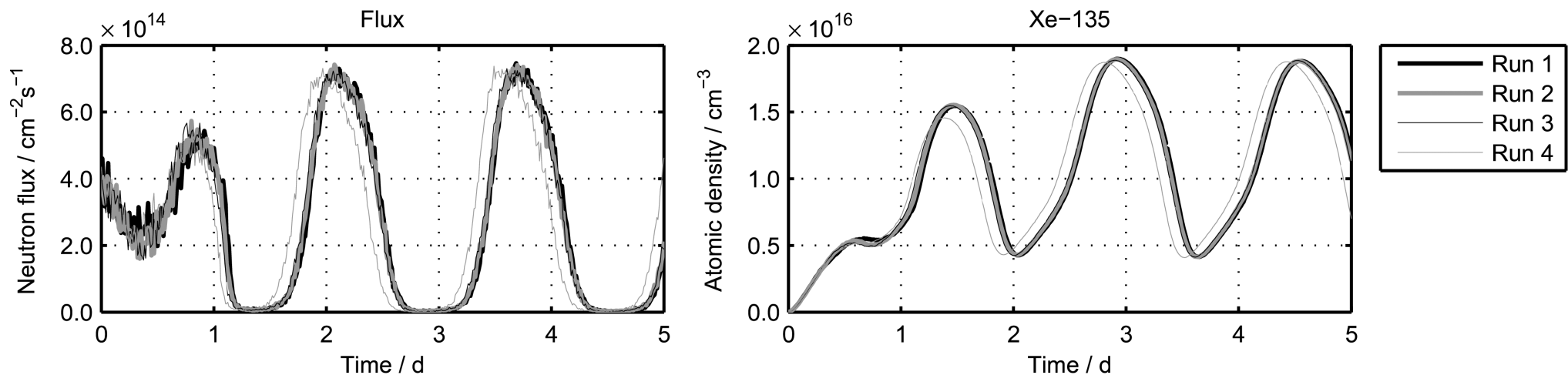
Results with normal steps

- 1-120 day steps → Numerical xenon oscillations
 - New methods of Serpent 2 are also affected
- Oscillations between predictor and corrector
 - Results look stable
 - In less extreme cases these oscillations might be difficult to notice



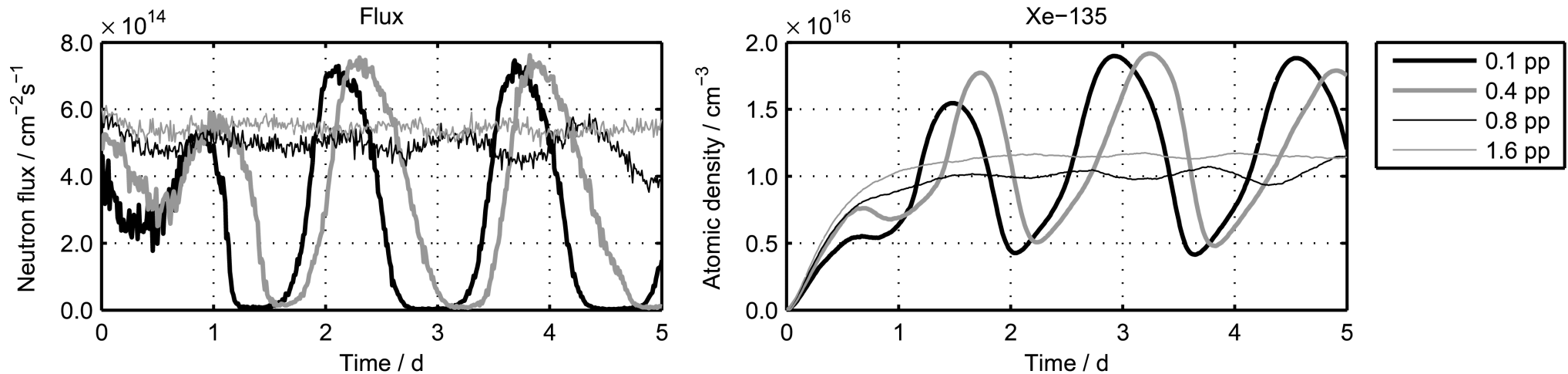
Results with very short steps (1)

- 15 min steps → physical xenon oscillations
- Reducing step length improves accuracy, nothing else
 - The results are accurate (for the model being solved)
- The model describes an oscillating system
 - No temperature feedback or reactor control system

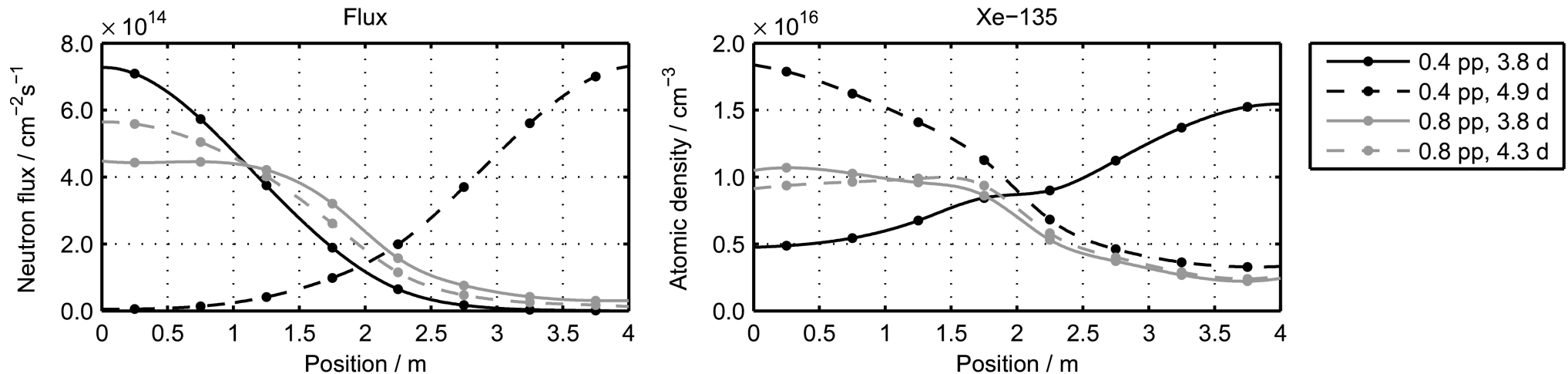


Flux and xenon concentration in segment 1 with 0.1 pp enrichment difference and 15 min steps. Four runs with different random number sequences.

Results with very short steps (2)



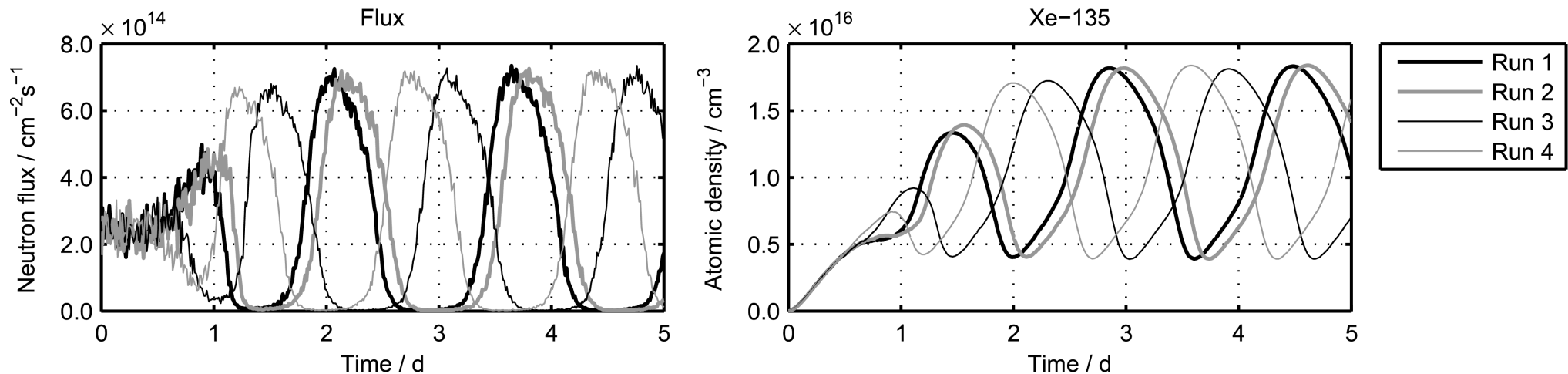
Flux and xenon concentration in segment 1 with different enrichment differences and 15 min steps.



Spatial distribution of the flux and xenon concentration at the extremes of the oscillations with 0.4 and 0.8 pp enrichment differences and 15 min steps.

Results with very short steps (3)

- Special case: no enrichment difference
 - Initial state is symmetric
 - The correct solution must be symmetric
 - Statistical variation breaks symmetry → oscillations
 - Easily handled by using the symmetry (2D geometry)



Flux and xenon concentration in segment 1 with 0 pp enrichment difference and 15 min steps. Four runs with different random number sequences.

Results with very short steps (4)

- The existing methods do work
 - Short enough steps → correct solution (to the model being solved)
 - 3h steps give a half-decent representation
 - Steps longer than the timescale of the solution → a mess
 - What else would you expect...
- The root of the instability problem is the model being solved
 - Adding temperature feedback and control models should help
- What we really want is stable results for the simple models
 - Force equilibrium
 - Represents the stabilizing effect of e.g. control system
 - Xenon-flux equilibrium at each neutronics solution
 - Xe-135 concentration calculated in the equilibrium calculation, not the depletion calculation.

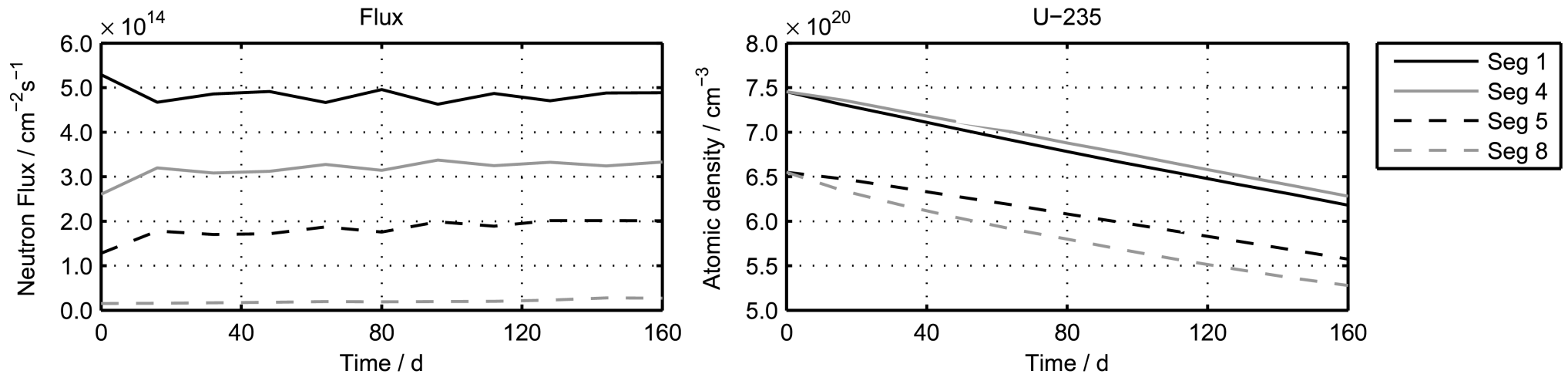
Equilibrium xenon

- Deterministic codes: another layer of wrapper to iterate equilibrium
 - Multiplies transport calculations required per step
 - Would be very slow with MC neutronics
- MC neutronics: possible to integrate equilibrium xenon calculation
 - Algorithms already exist (developed for other purposes)
 - Equilibrium xenon concentration and flux in one transport simulation
 - Only a minor slowdown
 - Can be used with any depletion algorithm and coupling scheme

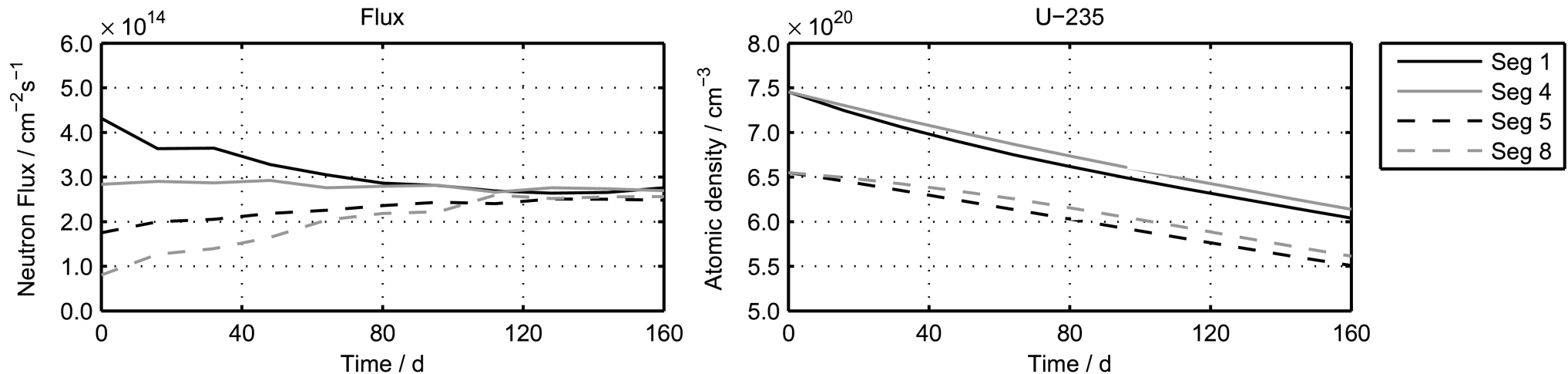
The equilibrium algorithm of Serpent

After each source cycle, xenon concentrations are set to saturated levels corresponding to the cross-sections collected during that cycle.

Equilibrium xenon results (1)



Flux and U-235 concentration with 0.4 pp enrichment difference and 16 day steps **without** equilibrium xenon



Flux and U-235 concentration with 0.4 pp enrichment difference and 16 day steps **with** equilibrium xenon

Equilibrium xenon results (2)

Average difference between local predictor and corrector fluxes as a fraction of the global mean flux with various enrichment differences and step lengths.

| | 1 d | 2 d | 4 d | 8 d | 16 d | 30 d | 60 d | 120 d |
|----------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| <i>Without equilibrium xenon</i> | | | | | | | | |
| 0.0 pp | 0.124 | 0.493 | 0.746 | 0.938 | 1.194 | 1.319 | 1.429 | 1.529 |
| 0.1 pp | 0.180 | 1.000 | 1.112 | 1.156 | 1.239 | 1.335 | 1.431 | 1.529 |
| 0.4 pp | 0.117 | 0.812 | 1.142 | 1.198 | 1.237 | 1.319 | 1.438 | 1.540 |
| 0.8 pp | 0.022 | 0.032 | 0.062 | 0.492 | 0.990 | 1.219 | 1.390 | 1.524 |
| 1.6 pp | 0.013 | 0.014 | 0.017 | 0.024 | 0.416 | 0.990 | 1.300 | 1.419 |
| <i>With equilibrium xenon</i> | | | | | | | | |
| 0.0 pp | 0.022 | 0.022 | 0.021 | 0.022 | 0.025 | 0.025 | 0.047 | 0.515 |
| 0.1 pp | 0.021 | 0.021 | 0.021 | 0.020 | 0.023 | 0.029 | 0.065 | 0.827 |
| 0.4 pp | 0.019 | 0.017 | 0.019 | 0.021 | 0.023 | 0.041 | 0.132 | 0.837 |
| 0.8 pp | 0.013 | 0.014 | 0.014 | 0.017 | 0.023 | 0.048 | 0.158 | 0.825 |
| 1.6 pp | 0.010 | 0.010 | 0.010 | 0.012 | 0.017 | 0.043 | 0.130 | 0.828 |

There is no exact or universal limit for how large a difference indicates instability!

Equilibrium xenon results (3)

- ≤ 30 day steps: oscillations disappear
- ≥ 60 day steps: numerical oscillations driven by fuel depletion
 - Limit depends on the problem being solved
 - Cannot be prevented with a similar approach
- Similar results with all coupling schemes available in Serpent 2
 - Exception: LE becomes unstable at 30 day steps
- Xenon is always forced to saturated level
 - Not applicable when non-saturated behavior is relevant
- The equilibrium algorithm of Serpent
 - Bias of the xenon concentration estimate might become a problem
 - Solution: Unbiased estimator. [3]
 - The algorithm of MC21 could be used instead. [4]

Equilibrium xenon results (4)

Average standard deviations of segment-wise fluxes in stand-alone transport calculation with various initial enrichment differences and burnup of 0 or 9.1 MWd/kgHM. The values are percent of mean global flux.

| Equilibrium xenon | | Fresh fuel | | Depleted fuel | |
|-------------------|--|------------|-------------|---------------|-------------|
| <i>0.0 pp</i> | | | | | |
| No | | 5.11 | (4.94 5.30) | 5.67 | (5.48 5.87) |
| Yes | | 1.66 | (1.61 1.72) | 2.30 | (2.22 2.38) |
| <i>0.1 pp</i> | | | | | |
| No | | 3.71 | (3.59 3.84) | 2.00 | (1.93 2.07) |
| Yes | | 1.80 | (1.74 1.87) | 1.80 | (1.74 1.86) |
| <i>0.4 pp</i> | | | | | |
| No | | 2.90 | (2.80 3.00) | 1.95 | (1.89 2.02) |
| Yes | | 1.48 | (1.43 1.53) | 1.53 | (1.48 1.59) |
| <i>0.8 pp</i> | | | | | |
| No | | 1.08 | (1.04 1.12) | 2.01 | (1.94 2.08) |
| Yes | | 1.08 | (1.05 1.12) | 1.76 | (1.70 1.82) |
| <i>1.6 pp</i> | | | | | |
| No | | 0.91 | (0.88 0.94) | 1.62 | (1.57 1.68) |
| Yes | | 0.79 | (0.77 0.82) | 1.44 | (1.39 1.49) |

The constant feedback from the equilibrium xenon calculation appears to improve convergence.

Conclusions

- Spatial stability is a real issue in large geometries
 - Oscillations may be difficult to notice from usual results
- The simulation models themselves are unstable
- Forcing flux and xenon concentration to remain in equilibrium helps
 - MUTUAL equilibrium, not just normal flux + saturated xenon level
 - Simple, lightweight, accurate (Can use any coupling scheme)
 - Step length limited by instability driven by other nuclides
- The method is available in Serpent (1 and 2)
 - “set xenon 1”
 - Prefer large neutron cycles
- There are other stabilizing schemes
- Gadolinium related instability might be harder to solve...

References

- [1] Dufek, J., Hoogenboom, J.E. *Numerical Stability of Existing Monte Carlo Burnup Codes in Cycle Calculations of Critical Reactors*. Nucl. Sci. Eng. 162, 307–311. (2009)
- [2] Dufek, J., Kotlyar, D., Shwageraus, E., Leppänen, J. *Numerical Stability of the Predictor-Corrector Method in Monte Carlo Burnup Calculations of Critical Reactors*. Ann. Nucl. Energy 56, 34–38. (2013)
- [3] Dumonteil, E., Diop, M.C. *Biases and Statistical Errors in Monte Carlo Burnup Calculations: An Unbiased Stochastic Scheme to Solve Boltzmann/Bateman Coupled Equations*. Nucl. Sci. Eng. 167, 165–170. (2011)
- [4] Griesheimer D.P. *In-Line Xenon Convergence Algorithm for Monte Carlo Reactor Calculations*. PHYSOR 2010. Pittsburgh, Pennsylvania, USA, May 9-14, 2010. On CD-ROM, ISBN 978-0-89448-079-9. (2010)

For a more detailed overview of the work presented here see

Isotalo A.E., Leppänen, J., Dufek, J. *Preventing xenon oscillations in Monte Carlo burnup calculations by forcing equilibrium*. Ann. Nucl. Energy 60, 78–85. (2013)

Thank you for your attention

Questions?