UPPSALA
UNIVERSITET

UPPSALA UNIVERSITET

UPPSALA UNIVERSITET

Serpent UGM - 2020

Use of Serpent Monte-Carlo code for development of 3D full-scale models and analysis of spent fuel quivers

Department of Physics and Astronomy, Division of Applied Nuclear Physics
Uppsala Universitet

Vaibhav Mishra and Zsolt Elter

UPPSALA UNIVERSITET

Agenda

1. Nuclear Safeguards
2. Quivers
3. Computational methodology
4. Flux around quivers

UPPSALA
UNIVERSITET

1. Introduction

Introduction: Nuclear Safeguards

Why

- Nuclear material should be used only for peaceful purposes
- Accountancy of nuclear materials

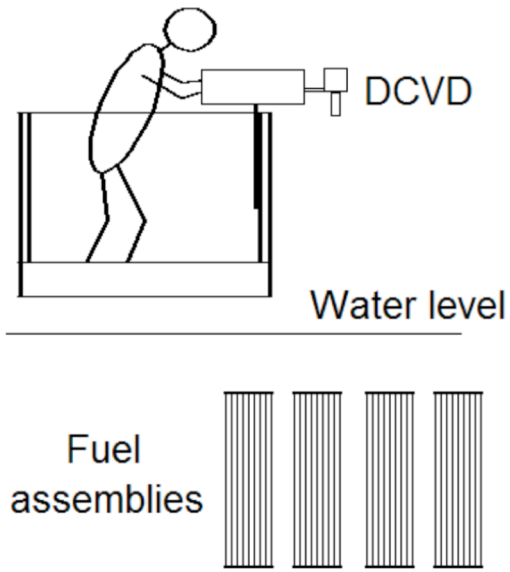
What

- With respect to verification of spent nuclear fuel, an inspector verifies operators' declarations
- Burnup, Cooling time, Initial enrichment, Fissile-content
- Gross defect and partial defect verification

How

- Isotopic composition of fuel depends on reactor operation and fuel history
- Non-destructive (gamma, neutron radiation, Cherenkov radiation)

Verification of SNF



A schematic of the measurement situation when using the DCVD. Image source: [1]

SFAT detector image from https://core.ac.uk/download/pdf/206032639.pdf

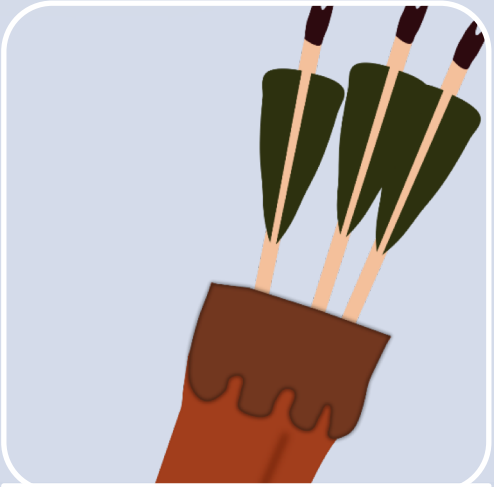
The new SFAT in its stainless steel container with the telescoping mechanism and ultrasonic positioning system. Image source: [2]

Fork detector image (Figure 3) from https://www.osti.gov/servlets/purl/1424458

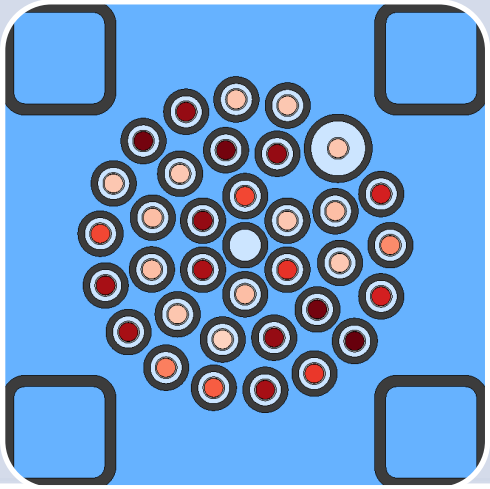
Fork detector measurement of a 17 × 17 PWR assembly being performed in Sweden. Image source: [3]

2. SNF Quivers

Quivers



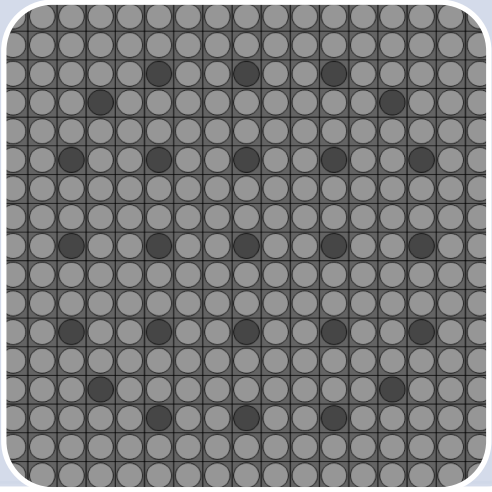
An archer's case for holding arrows



Cluster of stainless steel tubes to house damaged fuel

(cladding rupture)

Designed by Westinghouse



Identical dimensions as regular fuel.

No special handling equipment required.

Image source: [6]

Quiver specifications

1. Actual design may depend on request
2. But in Sweden there is one BWR and one PWR type
3. Temporary lid and long-term storage lid
4. After closure: water evacuated, filled with helium
5. New product (ca. 20 in Sweden)

PWR Quivers

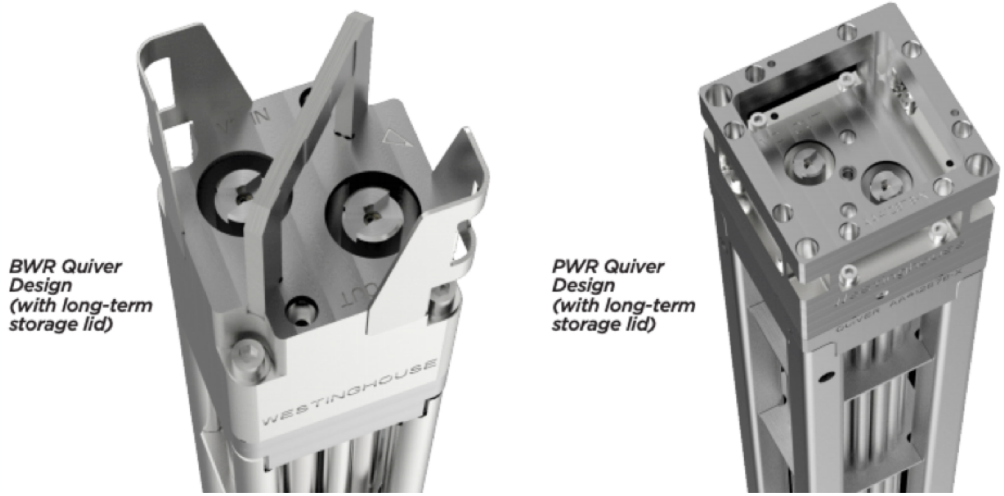
- Houses damaged PWR fuel rods
- Capacity: 30-60 PWR rods
- Overall dimensions identical to typical PWR fuel

BWR Quivers

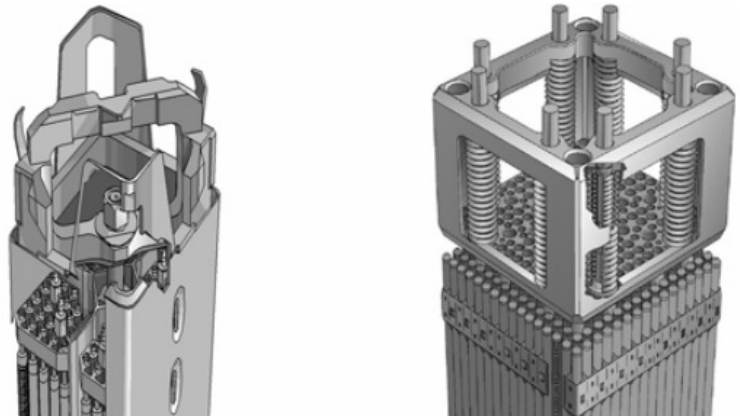
- Houses damaged/leaking BWR fuel rods
- Capacity: 14-28 BWR rods
- Overall dimensions identical to typical BWR fuel

Video on loading of LWR quivers courtesy of Westinghouse Electric : https://www.youtube.com/watch?v=SNtszjtYKzc

LWR quivers



Left: BWR quiver, Right: PWR Quiver from Westinghouse Electric AB Sweden. Image source: [4]

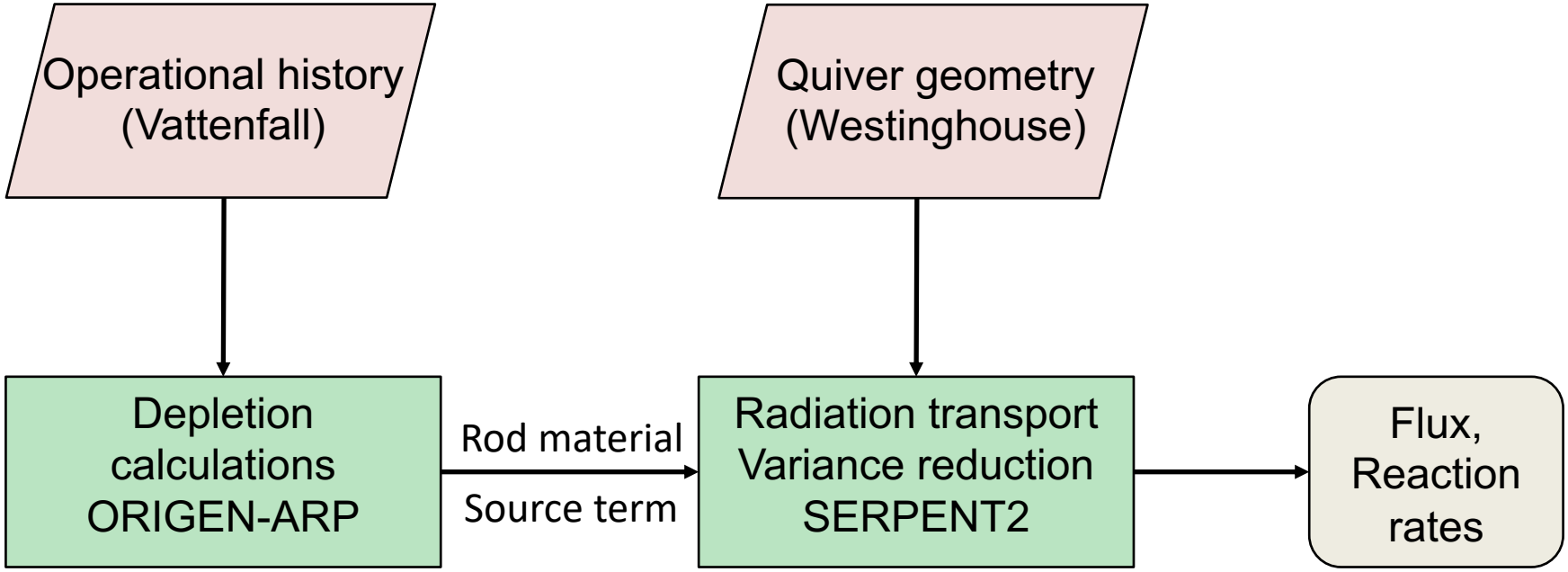


Left: BWR assembly head, Right: PWR assembly head. Image source: [5]

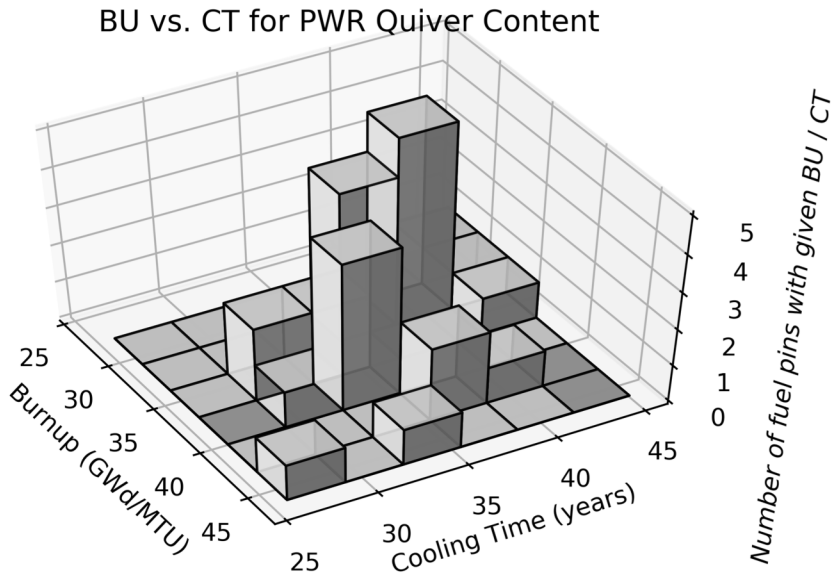
UPPSALA UNIVERSITET

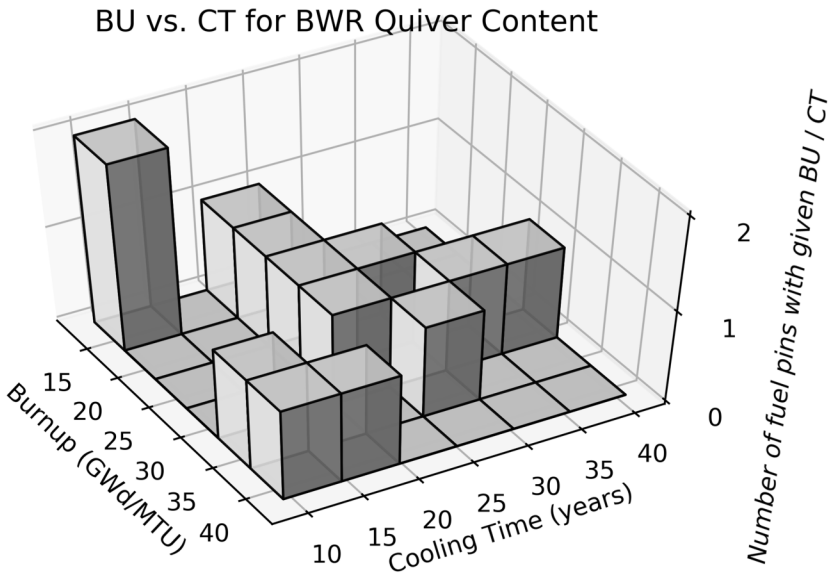
3. Methodology

Methodology



Quiver fuel content



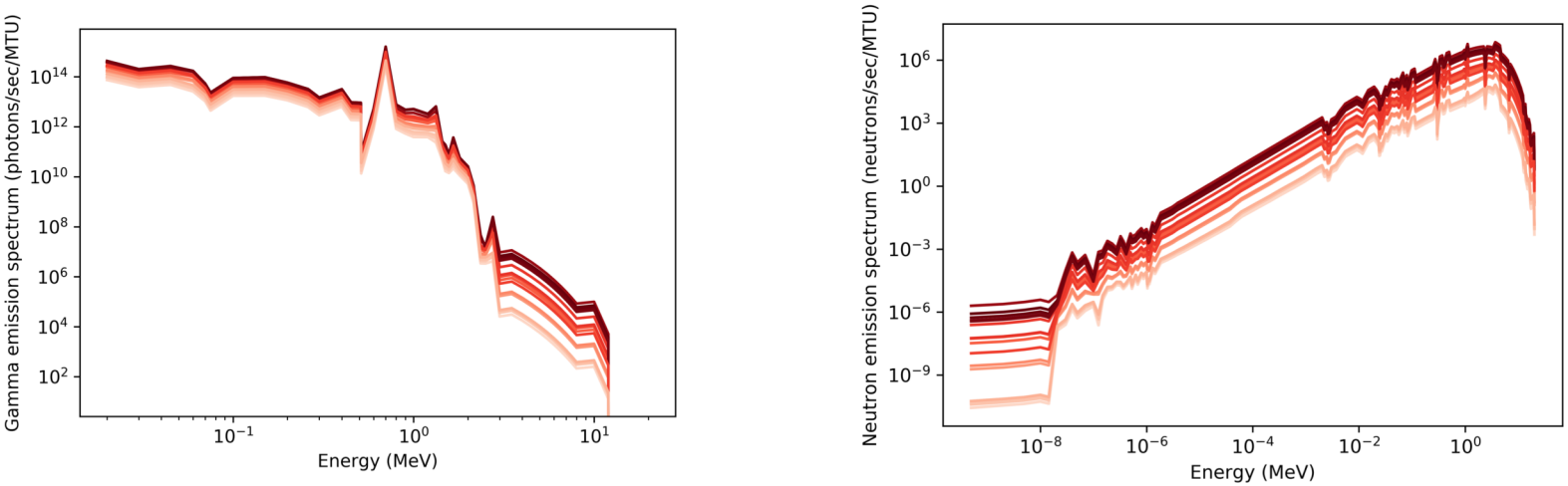


PWR and BWR quiver fuel content in BU-CT space.

PWR SFAT response

- Only the upper 50 cm of the rods hold active source
- Source energy distribution was omitted
- Monoenergetic 662 keV (emission rate from ORIGEN-ARP in the 600-700 keV bin) in each pin

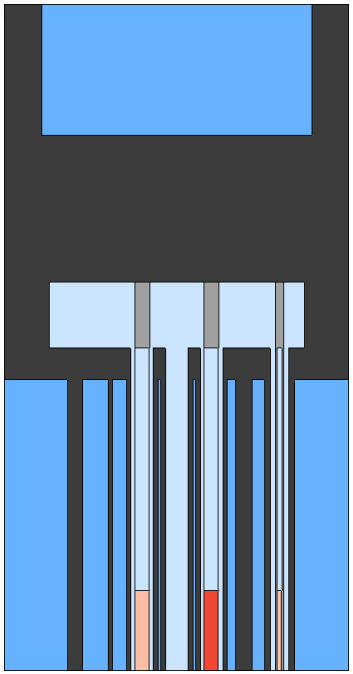
```
src srcA15 g sm UOX_E34 sx -0.801000 0.019000 sy 5.978000 6.798000 sz -70 -20 sw 0.010511 se 0.662
set srcrate 7615804185730.773438
```

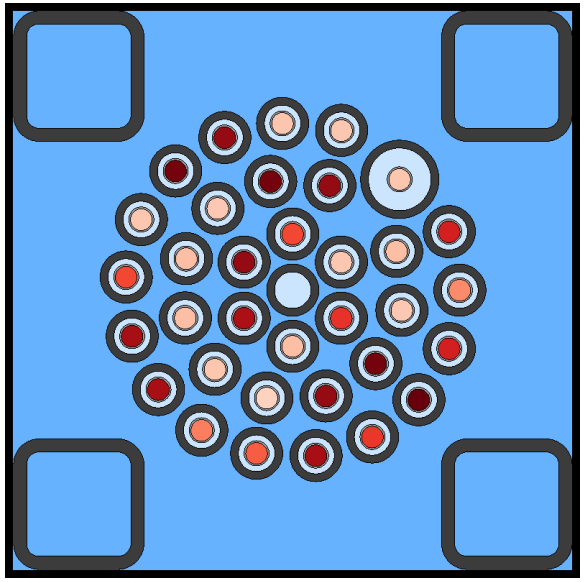


Left: Computed gamma emission spectrum from the fuel rods. Right: Computed neutron emission spectrum from the fuel rods.

Image source: [6]

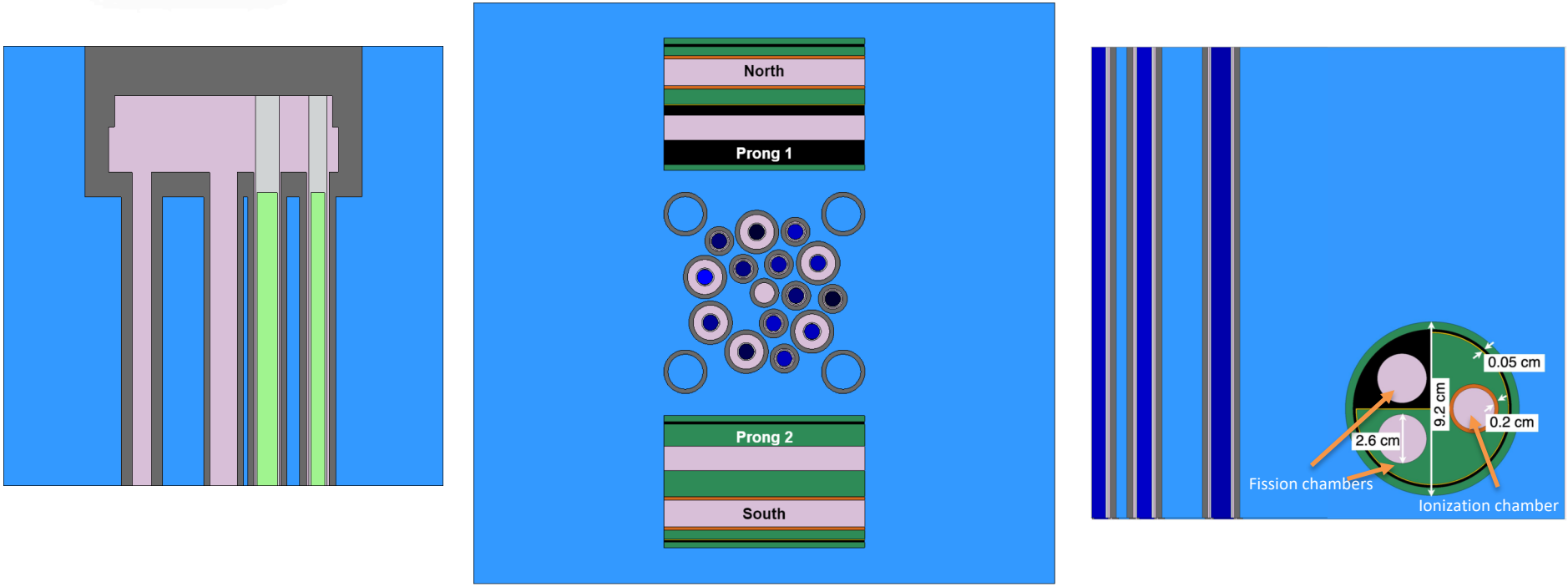
PWR quiver & SFAT model





Left: Cross-section of quiver showing SS lid. Right: Array of 35 fuel pins in quiver (top view). Bottom: The SFAT model used in the analysis.
Image source: [6]

BWR quiver & EURATOM Fork model

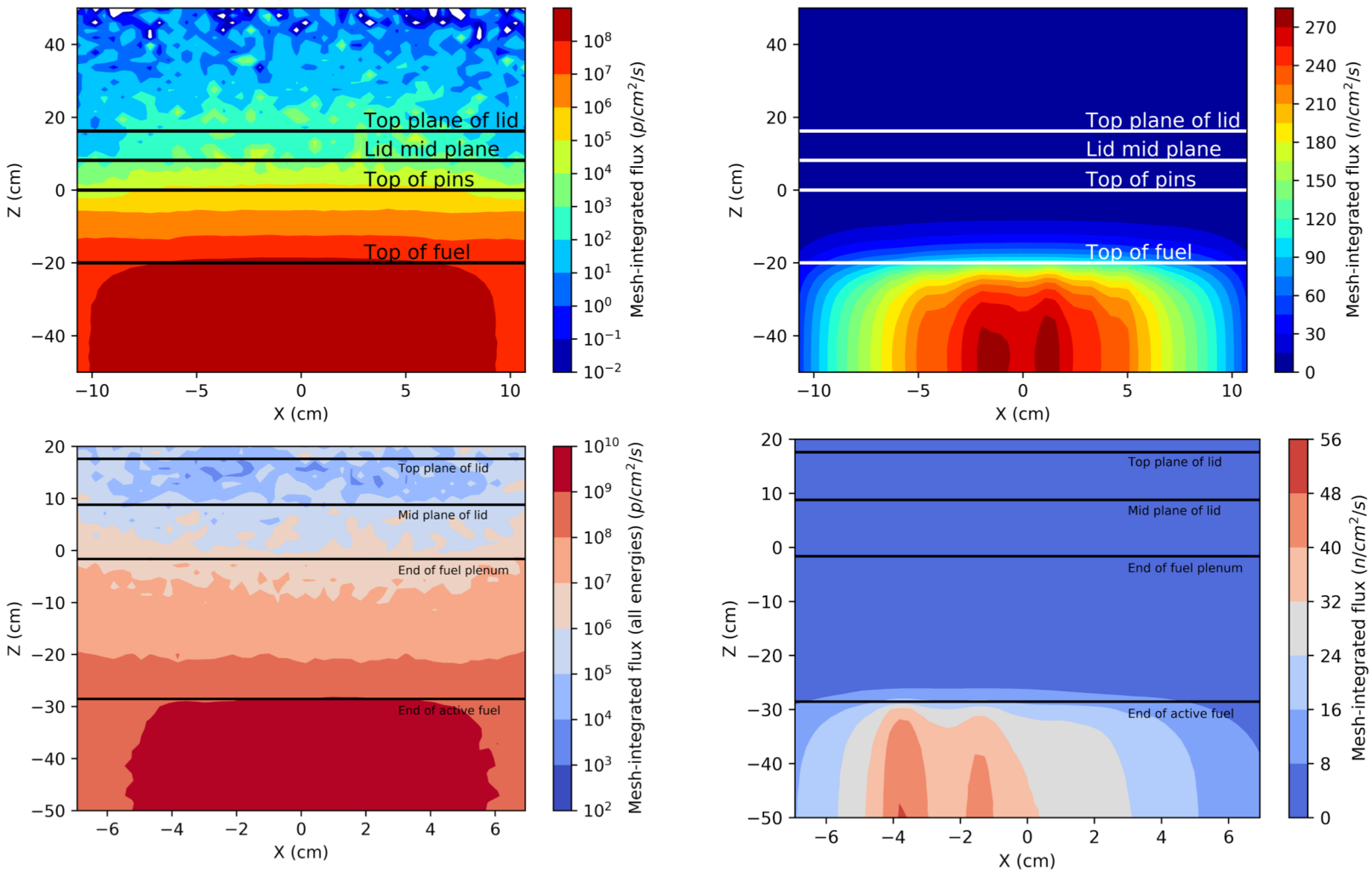


Left: BWR quiver with top lid. Center: Fuel tube arrangement inside the BWR quiver (top view) with the FORK arms positioned around it. Right: Cross-section of Fork arm showing gamma and neutron chambers. Image source: [7]

UPPSALA UNIVERSITET

4. Results

PWR and BWR flux mesh tally results



Top Left: Computed gamma flux from PWR quiver. Top Right: Computed neutron flux from PWR quiver. Image source: [6]
Bottom Left: Computed gamma flux from BWR quiver. Bottom Right: Computed gamma flux from BWR quiver. Image source: [7]

BWR Fork response

- Active source defined over entire fuel length
- Entire source energy distribution was used
- Use of appropriate reaction rate estimator with the help of ENDF MT reaction channel selectors
- Obtained estimates of fission rate and total dose rate with ICRP2.1 and ANSI/ANS flux-to-dose rate converters.

```
det detflux2 g dc cell_arm2_gammadet dr -100 fn1

fun fn1 1 1 1.00E-02 7.72E-12 1.50E-02 3.08E-12 2.00E-02 1.63E-12 3.00E-02 7.11E-13 4.00E-02 4.33E-13 5.00E-02 3.33E-13
6.00E-02 3.08E-13 8.00E-02 3.33E-13 1.00E-01 4.08E-13 1.50E-01 6.61E-13 2.00E-01 9.58E-13 3.00E-01 1.54E-12
4.00E-01 2.14E-12 5.00E-01 2.53E-12 6.00E-01 3.17E-12 8.00E-01 4.08E-12 1.00E+00 4.97E-12 1.50E+00 6.78E-12
2.00E+00 8.42E-12 3.00E+00 1.11E-11 4.00E+00 1.32E-11 5.00E+00 1.54E-11 6.00E+00 1.74E-11 8.00E+00 2.14E-11
1.00E+01 2.53E-11
```

BWR Fork response results

Calculated Parameter	Parameter Value
Dose rate	403 ± 41 Sv/h
Neutron counts	41 ± 3 cps (Channel A) 25 ± 3 cps (Channel B)

(a) Detector location: North

(b) Detector location: West

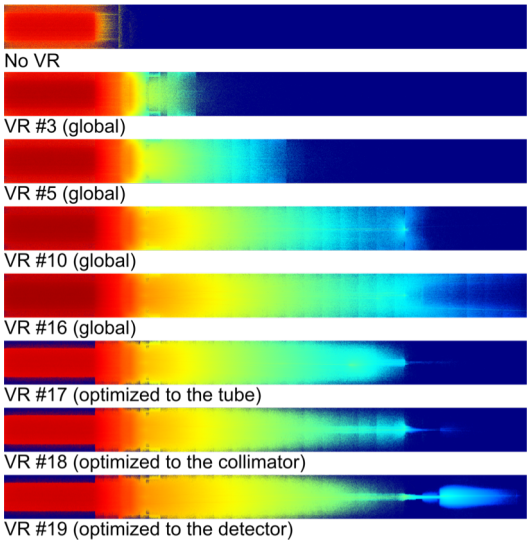
(c) Detector location: South

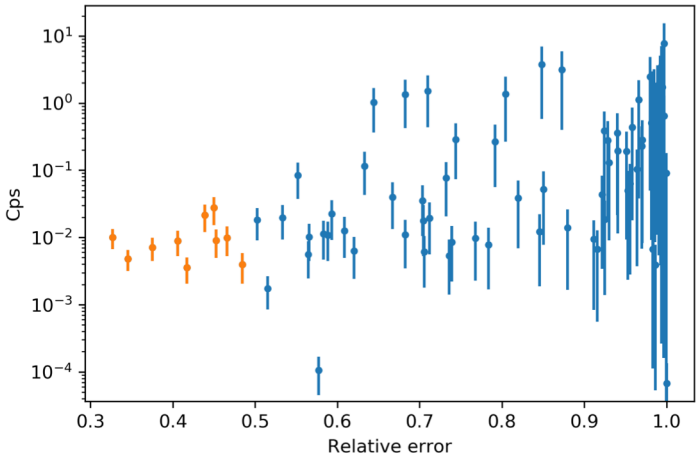
(d) Detector location: East

Computed rod-wise contribution to gamma flux (top bold text) and neutron flux (bottom bold-italicized text) at different positions of the Fork (marked with labels in each sub-figure). Contributions are shown as a percentage of total flux. Image source: [7]

PWR SFAT response results

- VR scheme was applied using weight-windows
  - 16 global variance reduction iterations
  - 1 step optimized for the steel tube
  - 1 step optimized for collimator slit
  - 1 step optimized for detector
- Unsure if VR scheme can be trusted due to low count rates (3 counts/5 mins). Needs refinement.
  - An F5 tally like semi-deterministic next event generator might be a better choice to get the response





Left: SFAT response after Implementation of various VR regimes. Image source: [6] Right: Variation of SFAT counts vs. relative error.

UPPSALA UNIVERSITET

Conclusions

- Serpent's versatility enabled easy set-up of full scale 3D models of fuel, source terms as well as overall quiver geometry
- Ability to compute fluxes and desired detector responses – of great benefit without much headache
- Availability of variance reduction routine allowed estimation of detector counts in very low flux environments
- From results for PWRq+SFAT: no detectable signal in SFAT and BWRq+Fork: measurable count rates for the Fork

UPPSALA UNIVERSITET

Thank you for your attention!

We would like to acknowledge the Swedish Radiation Safety Authority for supporting this work and for fruitful discussions. We would also like to thank Westinghouse Electric AB in Västerås, Sweden, for their interest in this work and for discussing quivers with us. We're also grateful to the authors, Sophie Grape, Peter Jansson, Li Balkeståhl, Erik Branger, Stefano Vaccaro and Marcus Hedberg for their contributions. Finally, we want to acknowledge Vattenfall for providing operational history for the spent fuel rods in the studied quiver.

UPPSALA UNIVERSITET

References

1. Branger, E. (2016). Studies of Cherenkov light production in irradiated nuclear fuel assemblies (Licentiate dissertation). Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-307952
2. SFAT image: https://core.ac.uk/download/pdf/206032639.pdf
3. Fork image: S. Vaccaro, I. C. Gauld, and J. Hu et al. Advancing the Fork detector for quantitative spent nuclear fuel verification. Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, spectrometers, Detectors and Associated Equipment, 888:202–217, 4 2018. ISSN 01689002.
4. Westinghouse Electric Company LLC. WESTINGHOUSE QUIVER: The simple, safe solution for handling and storing failed fuel rods and fragments, 2017. Link: https://www.westinghousenuclear.com/Portals/0/features/12823-Quiver-Digital-Handout-3-A4.pdf
5. Jacobsson Svärd, S. (2004). A tomographic measurement technique for irradiated nuclear fuel assemblies (Doctoral dissertation, Acta Universitatis Upsaliensis).
6. Zs. Elter, V. Mishra, S. Grape, E. Branger, P. Jansson, L. Balkeståhl, and M Hedberg. Development of a modeling approach to estimate radiation from a spent fuel rod quiver. In PHYSOR 2020 : Transition to a Scalable Nuclear Future, 2020. ISBN 978-1-5272-6447-2.
7. V. Mishra, Zs. Elter, S. Grape, P. Jansson, E. Branger, S. Vaccaro, and M. Hedberg “Estimating gamma and neutron radiation fluxes around BWR quivers for nuclear safeguards verification purposes”, accepted in JINST.