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Generic Criticality Considerations for Spent Fuel Pool Storage Racks under Beyond Design Basis Accident Conditions

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Outline

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- Calculation Methods
- Basic Configurations
- Postulated Accident Configurations
- Summary and Conclusions

Introduction

- After **Fukushima accident**, the **eight oldest NPP units** in Germany have been **permanently shut down** by political decision, accelerating nuclear phase-out
- Future emergency planning: Question **whether and if, under which circumstances, a criticality in a spent fuel pool (SFP) could occur**, with potential for Iodine release?
- German Nuclear Safety Standards Commission rule **KTA 3602**
  - Requires SFP criticality safety under respect of the **double contingency principle** (DCP)
  - Allows for **burn-up credit** and **partial boron credit** (not co-existant)
  - Demands **k_{eff} < 0.95 under normal and abnormal, and k_{eff} < 0.98 under all credible conditions**
- **Generic analyses** to evaluate which **beyond design configurations** could lead to an inadvertent criticality
- **Physical constraints**: changes in geometry, moderation or absorption conditions, or combinations of these need to eventuate
- **Postulated configurations** exceeding the requirements of the DCP have been investigated, irrespective of probability or possibility of occurrence or of a triggering event

Calculation Methods

- **Postulated accident configurations** exceeding the DCP
  → essentially **deterministic** analysis

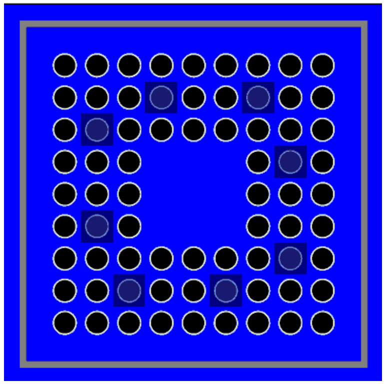
- **Criticality calculations**
  - SCALE 6.1
  - CSAS5 sequence
  - V7-238 cross section library
  - Typically 32 millions of neutron histories
  - Unit cells with reflective boundaries in all directions (if not stated otherwise)

- **Inventory determination** (in case of burn-up credit)
  - GRS KENOREST version 2008

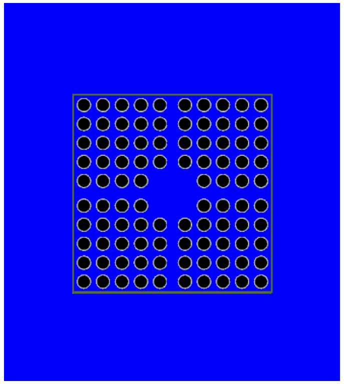
- All calculations “as is”, i.e. without corrections for bias and bias uncertainty

Basic Configurations (1): Reference Cases

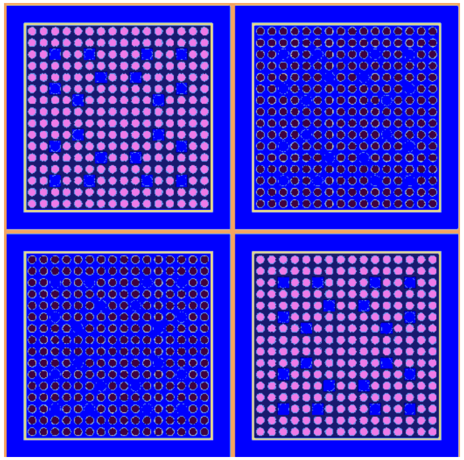
- **Generic SFP racks** for BWR and PWR assemblies, standard and compact design
- PWR: 2000 ppm soluble boron in coolant
- Initial enrichments up to 5.0 wt.-% ^{235}U
- Checkerboard arrangements of fresh and irradiated fuel (up to 40 GWd/tHM)
- By design: **k_{eff} < 0.95** for basic configurations



BWR compact rack unit cell



BWR standard rack unit cell



PWR compact rack, checkerboard

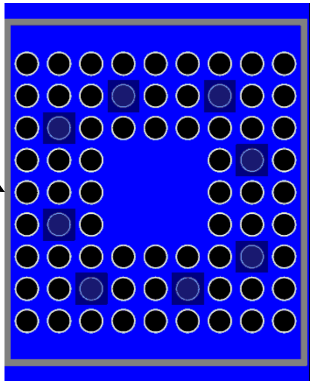
Basic Configurations (2): Required Changes to increase k_{eff} (Physical Constraints)

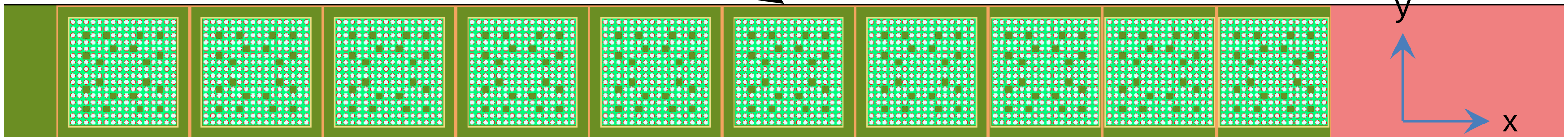
- Increase of SFP´s k_{eff} possible in case of changes in
  - **Moderation**
    - Increase of moderation in undermoderated systems (compact rack design)
    - Decrease of moderation in overmoderated systems (standard rack design)
  - Change in **geometrical configuration**
  - Reduced effectiveness or loss of **neutron absorbers**
    - Fixed absorbers (effectiveness moderation-dependent)
    - Soluble absorbers (PWR only)
  - **Burn-up credit**: Excess of admissible fissile content, or misplacement of one or more fuel assemblies with too low burn-up

- DCP: “(Process) Designs should, in general, incorporate sufficient factors of safety to require at least two unlikely, independent, and concurrent changes (in process conditions) before a criticality accident is **possible**.“

Postulated Accident Configurations (1)
Mechanically forced Reduction of Assembly Distance

- Mechanically forced **reduction of assembly distance** e.g. by massive impact or earthquake
- **Assembly structure itself remains intact**
  (assumption that rod compaction decreases moderation and hence reactivity)
- **Moderator remains present** (no loss of coolant assumed)
- Complete rack (infinite arrangement; here: BWR compact design)
- Few compacted assembly rows towards pool wall
  (here: PWR compact design)



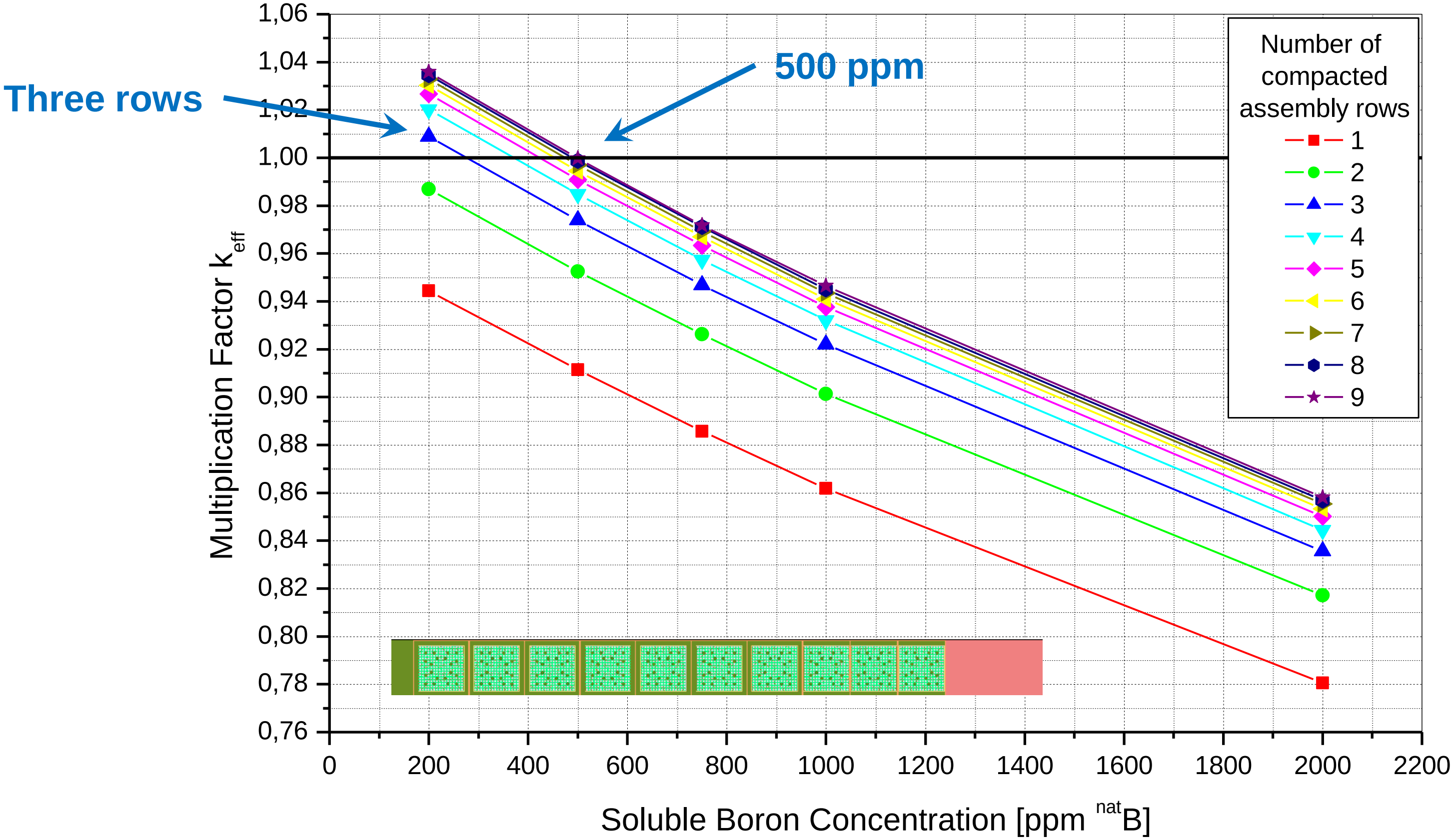


Postulated Accident Configurations (1)
Mechanically forced Reduction of Assembly Distance

- **Generic BWR compact rack**
  system remains subcritical even under fresh fuel assumption (fixed neutron absorber present)
- **Generic BWR standard rack**
  minimum burn-up of about 25 GWd/tHM for all assemblies
  system remains subcritical at maximum regular compaction i.e. minimum assembly distance in one direction
- **Generic PWR compact rack**
  system remains subcritical under fresh fuel assumption with more than 500 ppm boron in coolant, i.e. 25 % of nominal concentration under scope
- **Generic PWR compact rack**
  minimum burn-up of about 5 GWd/tHM for all assemblies
  system remains subcritical even without boron in coolant
- **Generic PWR compact rack and checkerboard allocation "fresh vs. irradiated"**
  minimum burn-up of about 10 GWd/tHM for all irradiated assemblies
  system remains subcritical even without boron in coolant

Postulated Accident Configurations (1)
Mechanically forced Reduction of Assembly Distance

- Variation of **number of compacted rods** and **boron concentration** in coolant

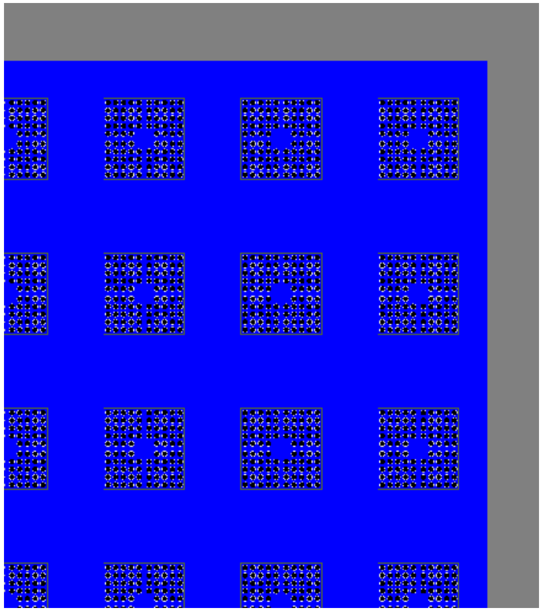


- In this generic model, at least three compacted assembly rows and a boron concentration below 500 ppm necessary for $k_{eff} > 1.0$

Postulated Accident Configurations (2)
Homogeneously and Heterogeneously reduced Moderator Densities

- In SFP compact rack design, reduction of moderator density decreases k_{eff}
- In SFP standard rack design, reduction of moderator density decreases neutronic decoupling, having potential for increase in k_{eff}

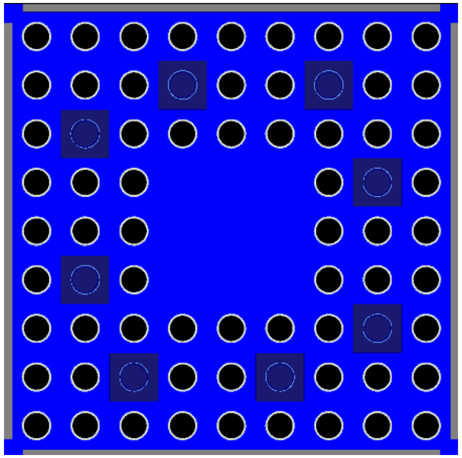
- **Generic Model**
  - Reactivity maximum at moderator of 20 % of full density water
  - $k_{eff} > 1.0$ for burn-up < 25 GWd/tHM
  - Drop of water level: 65 cm exposed to reduced moderator yield $k_{eff} > 1.0$

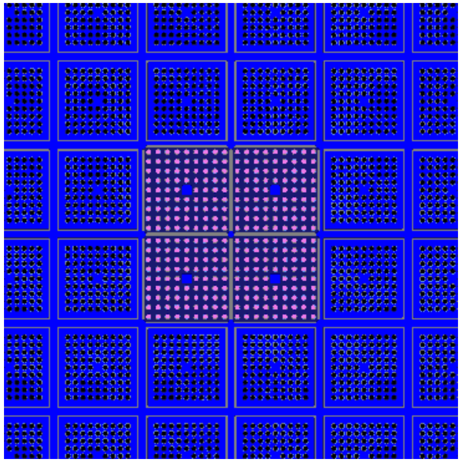


- **Reminder**
  - Water at 100 °C comprises ≈ 96 % of full density
  - Steam at 100 °C comprises ≈ 0.06 % of full density
  - 20% of full density conceivable in case of heavy bubbling; credible mechanism to cause this?

Postulated Accident Configurations (3)
Widening of Fuel Rod Pitch

- Modern LWR fuel assemblies are typically undermoderated
- **Regular widening of fuel rods** within a unit cell increases moderation ratio and hence reactivity
- Values $k_{eff} > 1.0$ for arrangements with more than four neighbouring unit cells with widened rod pitch
- However, **no credible triggering event** identified

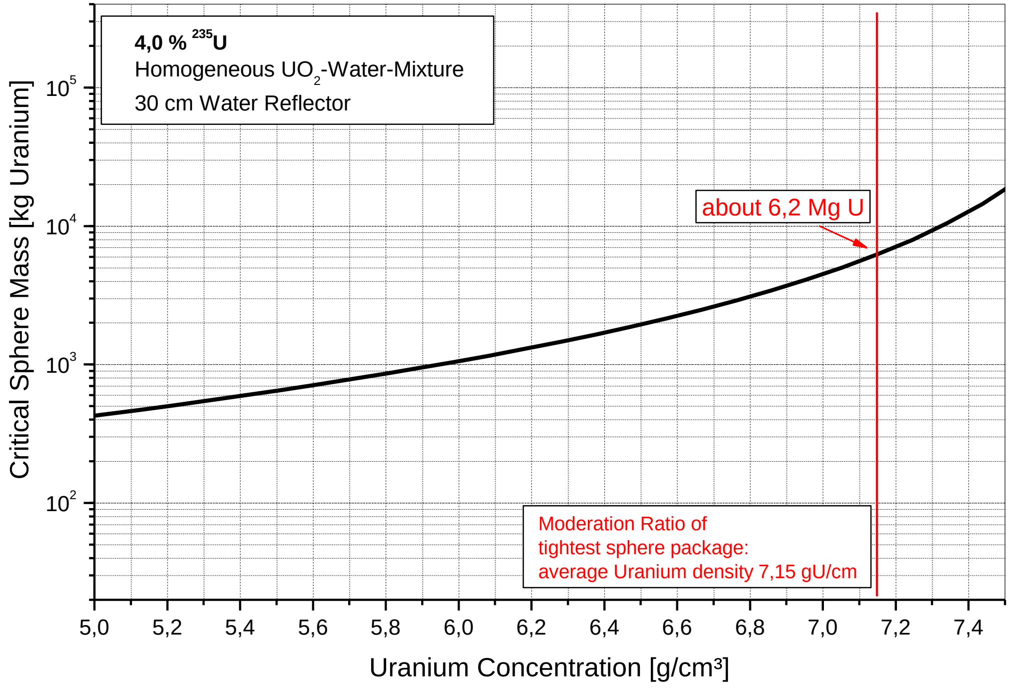




Postulated Accident Configurations (4)
Accumulation of Fissile Material at the Pool Bottom

- **Massive distortion or destruction** of parts of the fuel arrangement in the SFP
- Accumulation of fuel at the concrete bottom, moderator present
- Undefined mixture of fuel particles, structure material and coolant
- First **approximation**: Critical sphere mass of homogenized fuel – moderator – mixtures at given moderation ratio, taken from GRS “Handbook on Criticality”
- Resulting fuel concentration 7.15 g U / cm³, mass ≈ 6.2 Mg U (about 14 modern PWR assemb.)
- Approximation deficiencies
  - Mixture assumed homogeneous
  - Lack of structure material
  - Gross concentration estimation
- Triggering event, especially without loss of coolant in the pool?

Source: GRS "Handbuch zur Kritikalität", Draft 2013



Summary and Conclusions

- **Postulated beyond design accident configurations** have been analyzed for a variety of generic **spent fuel pool storage racks** and assembly designs
- Neither dedicated triggering events which could result in those configurations have been identified, nor have probabilities of occurrence of such configurations been determined
- A couple of **numerically critical or supercritical configurations** based on fresh or low irradiated fuel have been identified in this way., but **no credible mechanism to cause or trigger such configurations** have been figured out
- **No consequence analysis** has been performed due to large uncertainties in the definition of boundary conditions for transient analyses for such hypothetical configurations
- **No claim for completeness!**
- These assumptions and considerations provided a **contribution to a decision finding process** in order to evaluate certain aspects in the **emergency planning for NPP units in permanent shut-down mode**

Thank you very much for your attention!

Any questions?