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

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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 $k_{\text{eff}} < 0.95$ under normal and abnormal, and $k_{\text{eff}} < 0.98$ 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.-% $^{235}\text{U}$
- Checkerboard arrangements of fresh and irradiated fuel (up to 40 GWD/tHM)
- By design: $k_{\text{eff}} < 0.95$ for basic configurations
Basic Configurations (2): Required Changes to increase $k_{\text{eff}}$
(Physical Constraints)

- Increase of SFP’s $k_{\text{eff}}$ 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 $k_{\text{eff}} > 1.0$
Postulated Accident Configurations (2)
Homogeneously and Heterogeneously reduced Moderator Densities

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

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

**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 $k_{\text{eff}} > 1.0$ 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?

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**Diagram:**

- Critical Sphere Mass [kg Uranium] vs. Uranium Concentration [g/cm³]
- 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?