Criticality Safety Methodology for CASTOR® Spent Fuel Transport and Storage Casks

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Introduction

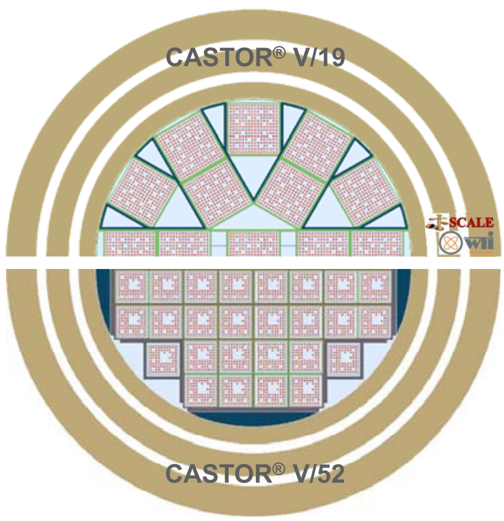
- CASTOR® casks are designed for transport and storage of
  - spent nuclear fuel (BWR and PWR) or
  - nuclear waste (HAW)
- Licensing for transport and storage is required:
  - Transport: IAEA regulations TS-R-1 and TS-G-1.1
  - Dry interim storage: German standards and regulations
- Double contingency principle is applied for dry interim storage
  - Separate evaluation of water ingress into cask and mechanical impacts onto the cask leading to deformations of cask internals and/or fuel assemblies (FA)
- Safety assessment of dry interim storage is covered by conditions of transport
- Methodology is exemplarily shown for CASTOR® V/19 and V/52 for spent PWR or BWR fuel

Basic requirements and criticality safety concept

- Calculation of maximum effective neutron multiplication factor k within condition: $k + \Delta k_U < 1 - \Delta k_S$
  - for normal and accident conditions of transport
  - Δk_U: sum of uncertainties of the calculation tool and the fissile system
  - Δk_S: subcriticality margin 0.05
- Subcriticality of CASTOR® V casks is based on:
  - Limitation of fissile content of the fuel
  - Geometrical positioning of the FA within a basket
  - Water traps (CASTOR® V/19)
  - Neutron absorbing structures

General concept

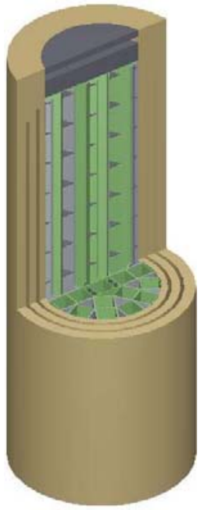
- Covering models are developed to cope with the variety of BWR and PWR FA designs:
  1. Criticality sensitivity analyses for a reference U- and MOX-FA
  2. If variation of a certain parameter leads to an increase in reactivity the same behaviour can be expected for the other fuel types
  3. Models of all fuel types are adjusted according to the possible tolerance range of this parameter
- Full, mixed or partial cask loadings with each FA type are considered



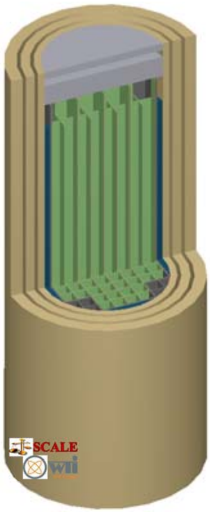
Criticality calculation code

- KENO from ORNL SCALE 5.1 code package

KENO VI
CASTOR® V/19



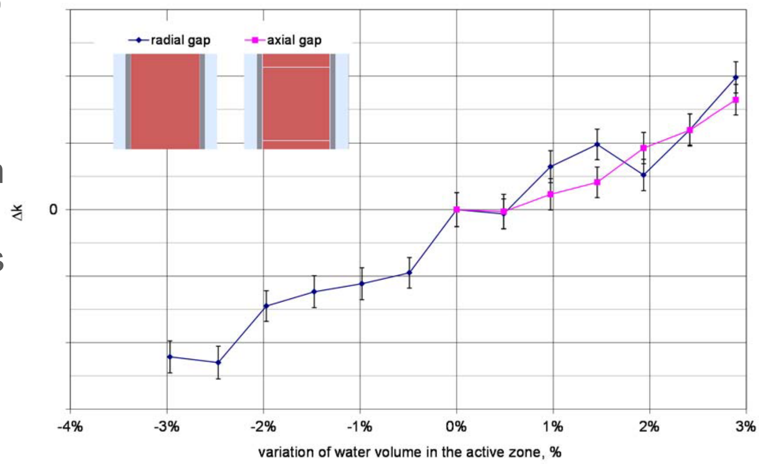
KENO V.a
CASTOR® V/52



- SCALE 238-group ENDF/B-V cross section data
- CENTRM/PMC for self shielded resonance cross sections

Specific model issues (1)

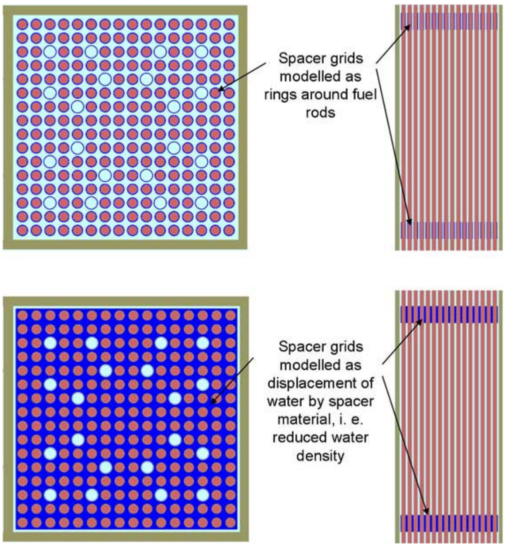
- Water flooding of gap between fuel pellets and clad
  - Requirement of German competent authority
  - Cover possible leakage of high burnup fuel rods and
  - Fuel pellet behaviour under irradiation (swelling and shrinking)
- Fuel pin model adapted to consider dishing and chamfering
  - Dishing and chamfering can be modelled as a fuel cylinder with reduced radius

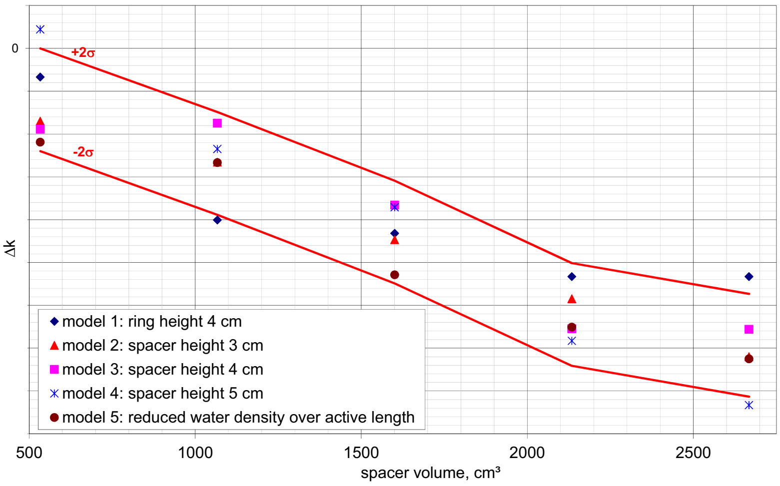


Specific model issues (2)

- For modelling of spacer grids only the water displacement has to be considered

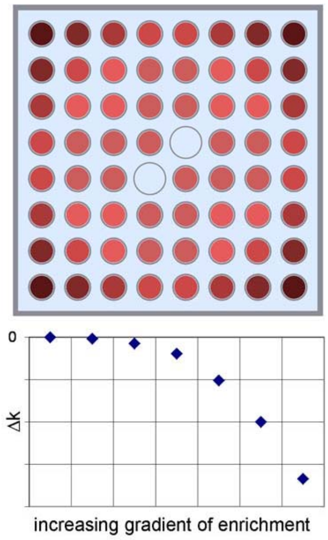
Model	Number of spacer grids	Height of spacer grids, cm	Spacer grid geometry
1	7	4	spacer material ring around each fuel rod
2 3 4	7 7 7	3 4 5	displacement of water by spacer material in pin unit cell, i. e. reduced water density
5	-	active length	displacement of water by spacer material in pin unit cell, i. e. reduced water density

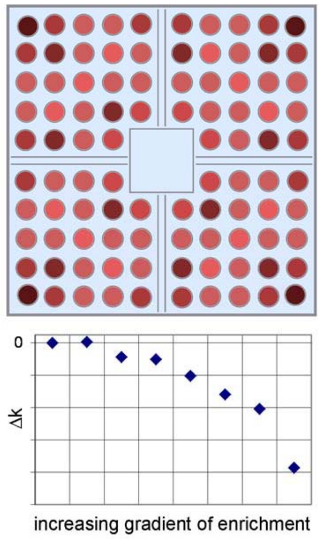




Specific model issues (3)

- Complex axial and radial BWR fuel enrichment
  - Applying conservatively the highest enrichment of any axial zone to the whole FA
  - Representing the FA by the radially averaged enrichment
    - Analyses for FA types with lowest and highest number fuel pins
    - FA type with lowest number of fuel pins has larger decrease of k

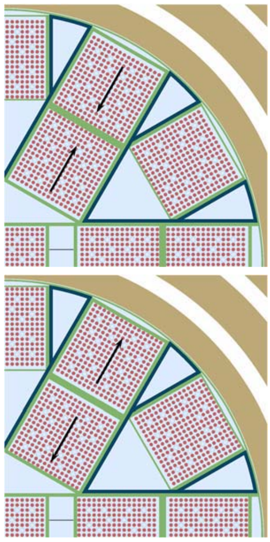




Covering models

- Normal conditions of transport
  - Analyses of tolerances of material compositions of structural materials
  - Variation of fuel pellet radius, clad inner and outer diameter
  - Variation of dimensions of FA structures
  - Axial and radial displacement of fuel assemblies within the basket positions
  - Analyses of inside and outside moderation

Radial displacement of FA



- Accident conditions of transport
  - Displacement of FA due to mechanical deformation of fuel basket
  - Deformation of FA due to mechanical impact
  - Fuel release and redistribution within the cavity after fuel rod failure

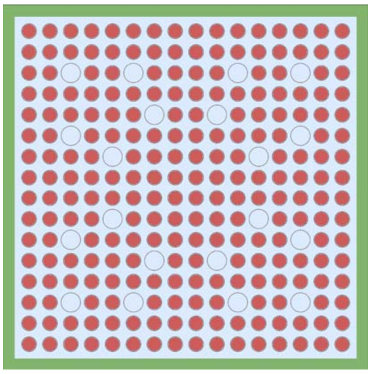
Deformation of fuel basket and FA

- Maximum deformation of fuel basket structures
  → no increase of k
- Deformation of FA depends on FA type and direction of impact
  - Horizontal impact: lattice contraction and decrease of k
  - Axial impact on BWR-FA:
    - Bottlenecking over 1st inter-grid space
    - Lattice expansion over 2nd inter-grid space
    - Slight bottlenecking over 3rd inter-grid space is possible
    - Deformation over 1st and 2nd inter-grid space follows a sine function
  - Axial impact on PWR-FA:
    - Lattice expansion over 1st inter-grid space („elephant footing“)

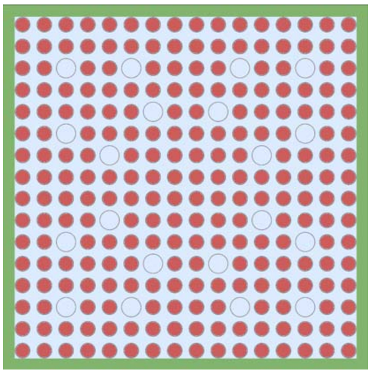
Deformation of FA – PWR model

- Uniform lattice expansion in 1st inter-grid space up to the maximum possible extension given by inner dimension of fuel basket channel
- Additional sensitivity analyses for uniform lattice expansion over 100cm assures subcriticality ($k + \Delta k_U < 1$)

Normal FA lattice

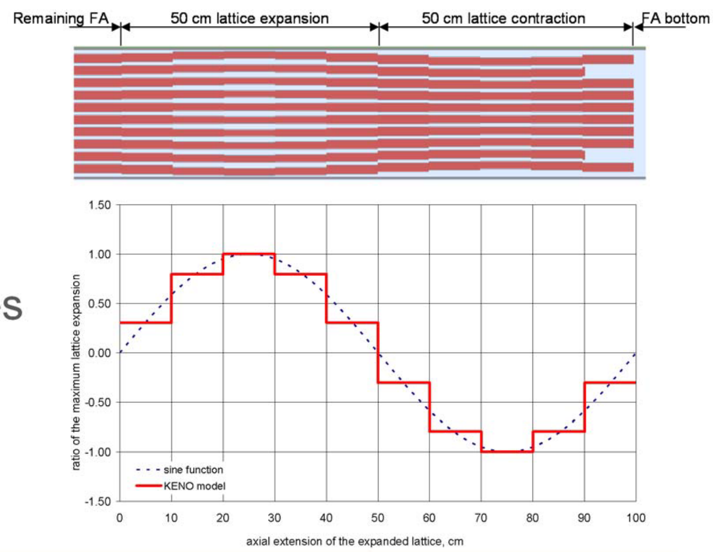


Expanded FA lattice



Deformation of FA – BWR model

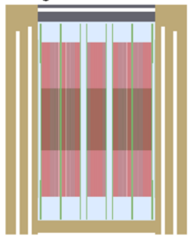
- Sine function of deformation is approximated
  - 10 axial segments over a height of 100cm
- Lattice expansion in 2nd inter-grid space up to the maximum possible extension given by FA channel dimension
- Possible lattice contraction in 3rd inter-grid space conservatively neglected
- Additional sensitivity analyses for uniform lattice expansion over 100cm: → subcriticality ($k + \Delta k_U < 1$) assured



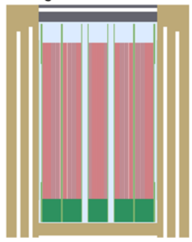
Fuel release after fuel rod failure

- Failure of all fuel rods leading to:
  - Release (local) of a fraction of the fuel material and
  - Free distribution of a homogeneous water-fuel mixture (sludge) within cask cavity
- Not enough space within cask cavity to form critical sphere or cylinder
  - Sludge within fuel lattice: decrease of k
  - Sludge at the end of active zone:
    - No coupling
    - No enhanced reflecting behaviour due to sludge
  - Sludge within water traps (PWR): no increase of k
  - Displacement of fuel pellets by water in fuel pins: no increase of k

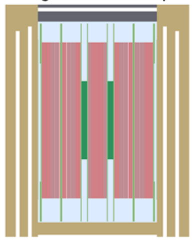
Sludge within fuel lattice



Sludge below active zone



Sludge within water traps



Burnup credit (BUC)

- BUC for PWR FA and for actinides (U+Pu) only
- Application of BUC follows German Standard DIN 25712
- Determination of Isotopic Correction Factors (ICF) based on analyses of commercial LWR fuel:
  - Calvert Cliffs, H. B. Robinson, Obrigheim, Trino Vercelles, Turkey Point and Takahama 3
  - Calculations performed with SCALE/TRITON
- Burnup dependent adaption of ICF for ^{235}U and ^{238}U
- Calculations for determining fuel composition at certain burnup are performed with SCALE/TRITON
  - Conservative irradiation conditions applied

Uncertainty Δk_U (1)

- Maximum of $k + \Delta k_U < 1 - \Delta k_S$ is calculated for both cask types for accident conditions of transport
- Δk_U is according to German Standard DIN 25712 the sum of the uncertainties due to:
  - Calculation of the nuclide inventory (Δk_N)
  - Consideration of fuel burnup (Δk_A)
  - Calculation tool (Δk_B)
  - Applied Monte-Carlo procedure (Δk_R)
  - Tolerances (Δk_T)
- Each contribution to Δk_U is expressed as the upper 95%/95% tolerance limit as long as no covering value or model is applied as done for Δk_N, Δk_A and Δk_T

Uncertainty Δk_U (2)

- Upper 95%/95% tolerance limit for Δk_R
  - Calculations for covering models for accident conditions of transport with random number variations are performed
  - Upper 95%/95% tolerance limit calculated according to:
    J.C. Neuber, *Some words about 95%/95% tolerance limit*, IAEA-TECDOC-1547, Vienna (2007)
- Uncertainty Δk_R determined by statistical analyses of benchmark experiments
  - Benchmark experiments taken from ICSBEP and NUREG/CR-6361
  - Adequacy of benchmark experiments evaluated by comparison of relevant parameters of criticality experiment and cask
  - Upper 95%/95% tolerance limit calculated according to J.C. Neuber (see above)

Summary

- Presented methodology of criticality analyses for CASTOR® casks
  - has been successfully applied to various licensing procedures
  - reflects state of the art for all ongoing CASTOR® cask licensing procedures
  - will be adapted to progress of scientific and technological knowledge and to further development of licensing requirements
- Methodology has been developed over last 15 years at WTI/GNS