Aspects of Spent Fuel Behavior Assessment for Transport Packages

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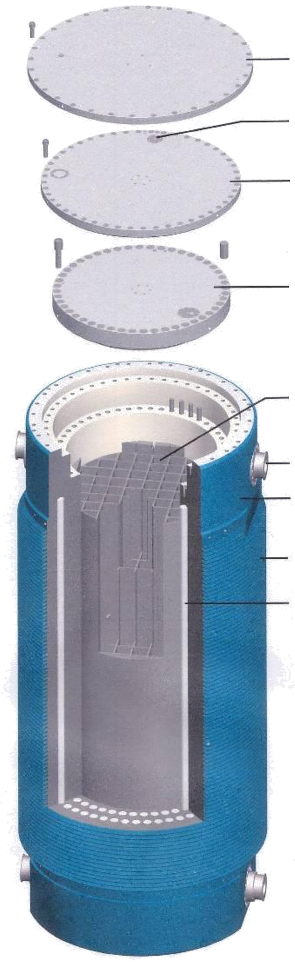
Introduction / Authorities, DPC

Competent authorities for package design approval procedure in Germany

- Federal Office for Radiation Protection (**BfS**)
  (shielding and criticality safety)
- **BAM** Federal Institute for Materials Research and Testing
  (mechanical, thermal, containment safety assessment and quality assurance program)



Source: GNS

Dual purpose casks in Germany

- Interim storage and transport
- Up to 21 PWR or 52 BWR fuel assemblies
- Maximum average burn-up 65 GWd/t_U
- Closed by bolted lid systems
  (usually double barrier)
- Metallic gaskets (elastomeric gaskets for testing)

Protection Goals

Regulatory transport conditions (IAEA)

- **Routine** conditions of transport **(RCT)**
  - Regular transport, no incidents
- **Normal** conditions of transport **(NCT)**
  - Minor incidents
  - Test e.g.: 0.3 m drop test onto unyielding target
- **Accident** conditions of transport **(ACT)**
  - Impact and thermal loads
  - Test sequence e.g.: 9 m free drop onto unyielding target + 1 m puncture drop + 30 min. fire at 800 °C

9 m drop test

Compliance with:

- Activity release limits ❾ containment analysis
- Maintain subcriticality ❾ criticality safety analysis

Spent fuel assessment

Potential cladding failure

❾ Activity release into cavity

❾ Impact on:

- Containment analysis (BAM)
- Criticality safety (BfS, mechanical assumptions BAM)

For assessment knowledge needed about:

✦ **Loads (e.g. by drop tests) passed via:**
❾ impact limiter ❾ cask body ❾ basket ❾ fuel assemblies ❾ fuel rods

Complex mechanical interaction ❾ **limited knowledge**

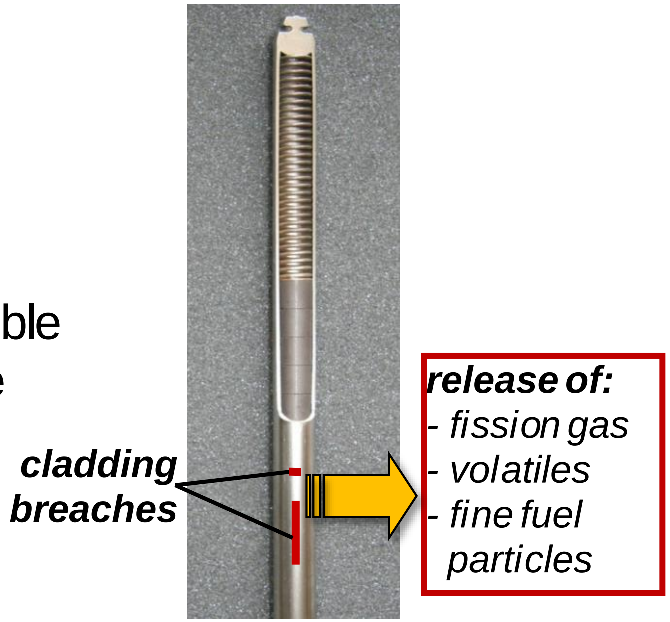
✦ **Material behavior, wide range depending on:**
Cladding alloy, operational and storage history, burn-up, oxidation, possible hydride reorientation, etc. ❾ **limited knowledge**

❾ **BAM uses enveloping approaches!**

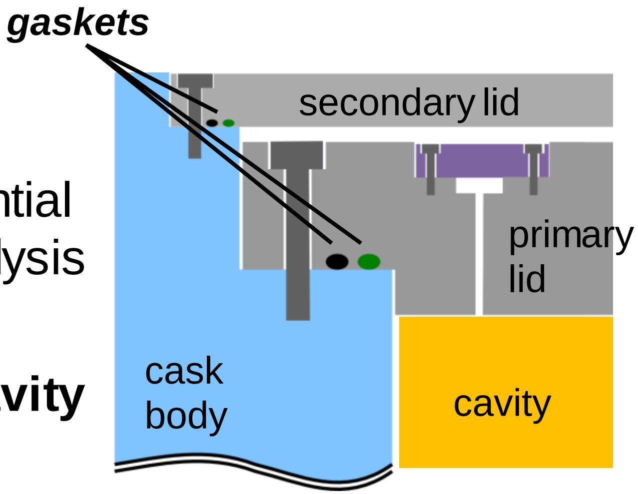
Containment analysis

- **Activity release criteria (IAEA SSR-6)**
  - For **NCT** 10^{-6} A_2 per hour,
  - For **ACT** 10 A_2 per week for krypton-85, 1 A_2 for all other radionuclides

- Direct measurement of activity release not feasible ❾ relation to equivalent **standardized leakage rates**



- **Cladding as first barrier of containment**
- **Cladding breaches** lead to:
  - Activity release into cask cavity (gas, volatiles, fine fuel particles)
  - Escape of gases and volatiles through potential leak in gasket possible ❾ containment analysis



- Assumptions for **radioactive material in the cavity** required!

BAM assumptions for radioactive material in the cavity

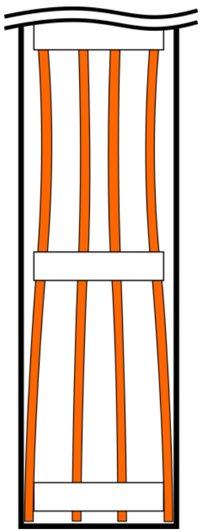
- Failure rates of fuel rods
  - Normal conditions of transport (e.g. 0.3 m drop test)
    - 3 % for burn-up ≤ 55 GWd/t_U (based on NUREG/CR-6487 report)
    - 100 % for burn-up ≤ 65 GWd/t_U
  - Accident conditions of transport (e.g. 9 m drop test)
    - 100 % for all burn-up (based on NUREG/CR-6487 report)
- Released fractions of fuel rod content
  - 15 % of fission gas
  - 0.02 % of volatiles
- Source term (BfS)

❾ Amount of released fissile products in cavity

❾Activity release calculation based on standard design leakage rates of gasket

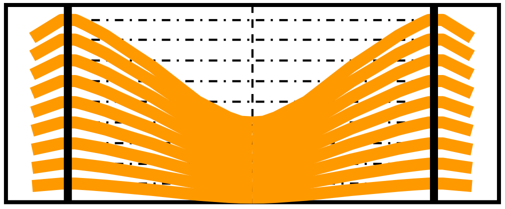
Assumptions for criticality safety analysis

Impact on criticality safety
(ACT, assumption of water in containment)



Expansion of lattice spacing

- Expansion of lattice spacing
  (e.g. buckling of fuel rods during 9 m vertical drop)
  ❾ increased moderation ratio



Breakage of fuel rods

- Fuel rod breakage
  (e.g. breakage of fuel rods during 9 m lateral drop)
  ❾ fissile material in cavity

- Limited data on mechanical behavior of fuel assemblies
  → **simplified enveloping approach**

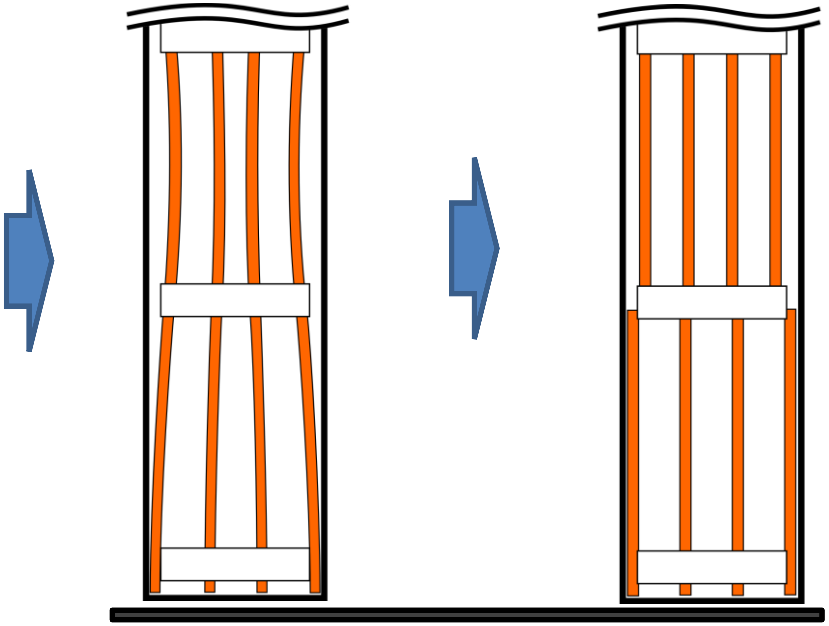
Assumptions for criticality safety analysis

Expansion of lattice spacing

- **9 m vertical drop test**
  - Induced inertia forces usually higher than buckling forces
  - Dynamic buckling of fuel rods not predictable
  - **Assumption of covering deformation state** (unfavorable for criticality safety)

Example of PWR fuel response:

9 m vertical drop test



Possible buckling *Covering deformation state*

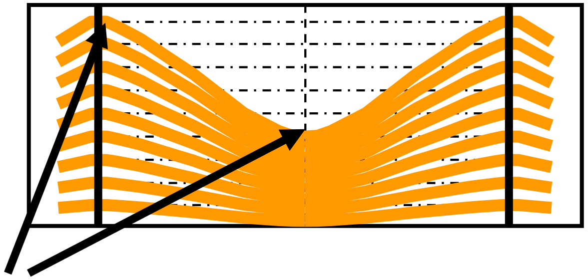
- **Input for criticality safety analysis (BfS)**

Fuel rod breakage

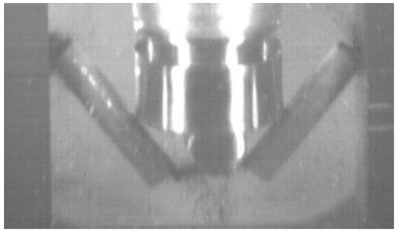
- Estimation of fissile material in cavity
- BAM assessment:
  - Deformation state
    (for 9 m drop)
    ❾ fracture points of fuel assembly
    (mechanical approximation with beam theory)
  - Amount of released fissile material per fracture point
    (based on hot cell experiments)

❾ Total amount of released fuel in cavity

9 m lateral drop test



Breakage?



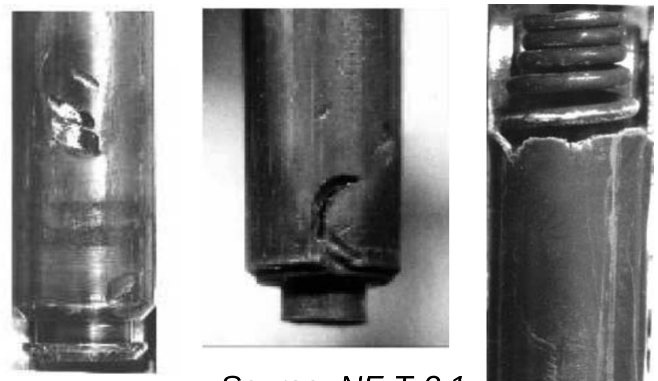
Hot cell tests on fuel rods
Source: Papaioannou et al: Jahrestagung Kerntechnik, 12-14 May 2009

❾ **Input for criticality safety analysis (BfS)**

Encapsulation of Defective Fuel Rods

Defects on fuel rods during NPP operation

- ✦ **IAEA NF-T-3.6: “**Management of Damaged Spent Nuclear Fuel”
- ✦ **IAEA NF-T-2.1: “**Review of Fuel Failures in Water Cooled Reactors”

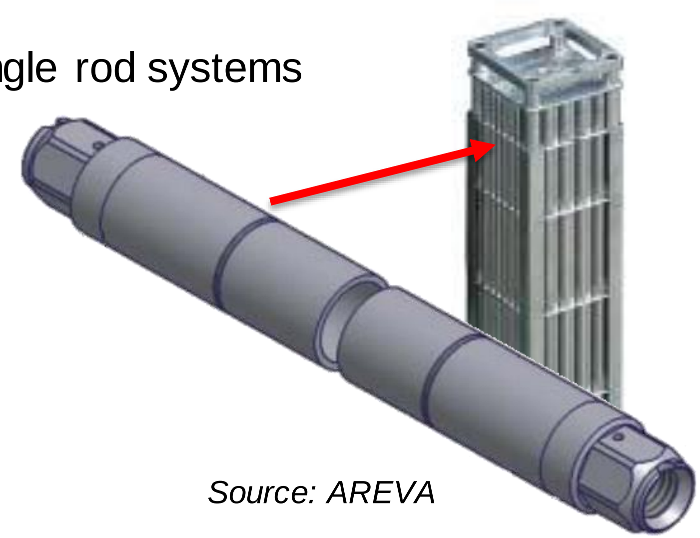


Source: NF-T-2.1

- ❾ **Fuel rods extracted and separated**
- ❾ **Encapsulation for transport and storage**

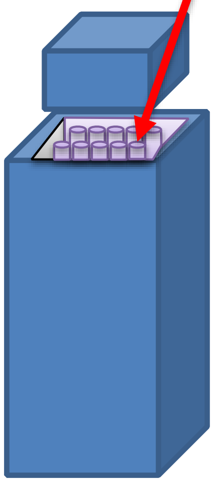
Encapsulation Types:

Single rod systems



Source: AREVA

Multi rod systems



principal sketch

Encapsulation of Defective Fuel Rods

- **Transport requirements:**
  - Established inside of **licensed spent fuel packages**
  - Package design not affected negatively

    ❾ Similar mechanical behavior as fuel assemblies

- **Challenges:**
  - Different sealing system (usually permanent by welds)

    ❾ Drying, sealing and tightness testing after loading as part of the approval process
  - Higher stiffness than fuel assemblies

    ❾ Damping structures required

- **Advantages:**
  - Well-known mechanical characteristics

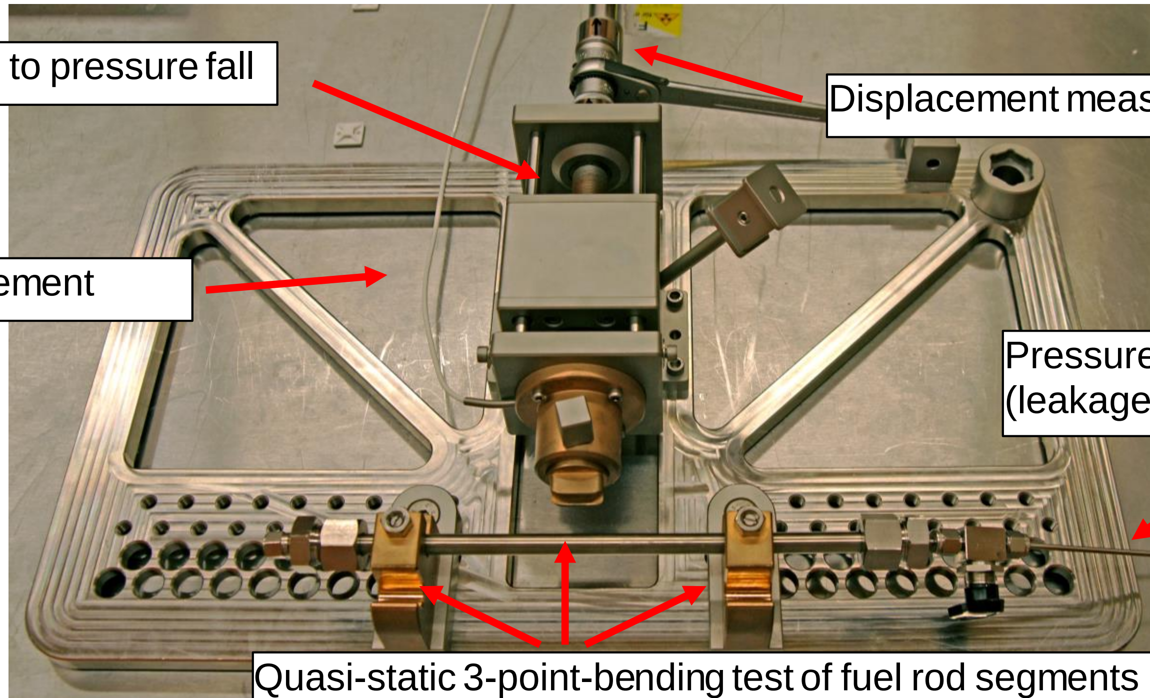
    ❾ Precise prediction of the encapsulation behavior under transport conditions

Collaboration of BAM with Institute for Transuranium Elements (ITU)

Karlsruhe, Germany

- **Motivation:** Knowledge gap of material behavior of (high burn-up) fuel rods
- Hot cell facilities at ITU ❾ **Joint proposal**

Source: ITU



- Comparison with loads of 0.3 m drop test
- Extension to ACT currently under discussion
- **Cold testing has started!**

Conclusions

- BAM as one of two competent authorities for package design approval procedure in Germany

- Spent fuel assessment for transport packages
  - Limited knowledge about spent fuel behavior (esp. high burn-up)
    ❾ enveloping approaches needed
  - BAM approaches for
    - Containment assessment
    - Assumptions for criticality safety analysis
    - Encapsulations of defective fuel rods

- R&D
  - Cooperation BAM/ITU
  - 3-point bending test of pressurized spent fuel rods