Mechanical Safety Analysis for High Burn-up Spent Fuel Assemblies under Accident Transport Conditions

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Outline

- General description of the problem
- Simplified method for assessment of fissile material release
- Parameters and their experimental basis
- Conclusions

Loading conditions and kinds of deformations

- <u>Horizontal (side) drop</u>

- bending of the rods under transversal inertia loads
- pinch forces due to rod-to-rod / rod-to-spacer grid interactions
- lattice pitch tends to reduce
- …

- <u>Vertical (end) drop</u>

- axial loading can lead to buckling of the fuel rods
- pinch forces due to rod-to-rod / rod-to-spacer grid interactions
- permanent expansion of lattice in the lower sections due to post-buckling bending or interactions with deforming nozzles
- …

- Combinations of above deformations and loads in <u>other drop orientations</u>

Failure modes

(*according to Sandia Report SAND90-2406)*

(I) transverse tearing initiated under bending loading

(II) extension of mode (I) to partial or complete rod breakage

(III) longitudinal tearing due to pinch load (e.g. rod-to-rod interaction)

Discussion of approaches

- Possibilities for a direct experimental investigation of the behaviour of the content within the cask are very limited.
- Sophisticated numerical approaches with detailed simulation of fuel assemblies can be useful for phenomenological understanding, but there are no adequate experimental data for their verification.
- For mechanical analysis in the context of an approval procedure a simplified methodology is generally preferred, which at the same time is sufficient for assumptions in nuclear safety demonstration.
- Combination of such simplified methods and component tests, e.g. with fuel-in cladding tubes, is of decisive importance.

Simplified approach

Relevant loading conditions for assessment of fissile material release

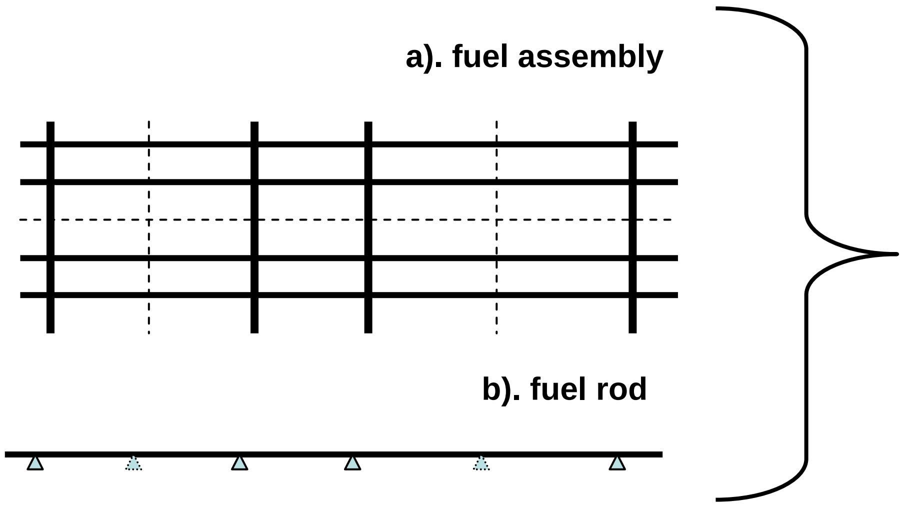
- Rod breakage under bending with rod separation in two or more parts has got the highest potential for release of fuel particles.

- If a number of rod breakages and fissile material release is conservatively estimated for this loading case, the contribution of other failure modes to released fuel can be neglected.

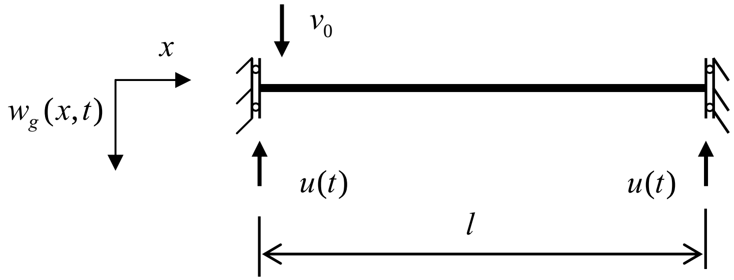
- As a typical example of impact induced bending deformations, the fuel rod response during a side drop of a cask will be analysed.

Assumptions and simplifications

- Interactions between the fuel rods of fuel assembly will be neglected first, and a free deflection of a single rod will be considered.
- Analysis will be limited only to one rod inter-grid section clamped at both supports.
- Rod section will be assumed as straight uniform composite beam with elastic material behaviour.



c). rod section

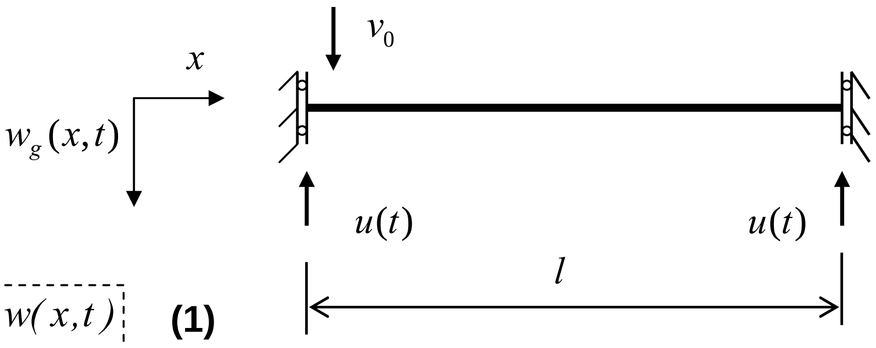


-flexural rigidity of the fuel rod (C-cladding, P-pellets)

$$(E\,I)_\Sigma = E_C(I_C + \frac{E_P}{E_C} I_P) = E_C I_\Sigma$$

-mass per length $m_x = m/l$

Dynamic lateral response of beam



Equation of motion (kinematic exitation):

$$w_g(x,t) = u(t) + w(x,t) \qquad \textbf{(1)}$$

$$(EI)_\Sigma \frac{\partial^4 w_g(x,t)}{\partial x^4} + m_x \frac{\partial^2 w_g(x,t)}{\partial t^2} = 0 \quad \Rightarrow \quad (EI)_\Sigma \frac{\partial^4 w(x,t)}{\partial x^4} + m_x \frac{\partial^2 w(x,t)}{\partial t^2} = -m_x \ddot{u}(t)$$

initial and boundary conditions:

$$t = 0, \quad w_g(x,0) = 0; \quad \dot{w}_g(x,0) = -v_0 \qquad\qquad t = 0, \quad w(x,0) = 0; \quad \dot{w}(x,0) = 0$$

$$x = 0, \quad w_g(0,t) = w'_g(0,t) = 0 \qquad\qquad x = 0, \quad w(0,t) = w'(0,t) = 0$$

$$x = l, \quad w_g(l,t) = w'_g(l,t) = 0 \qquad\qquad x = l, \quad w(l,t) = w'(l,t) = 0$$

Exact solution:

$$w(x,t) = -\sum_{i=1}^{\infty} X_i(x) \int_0^l X_i(x)dx \, \frac{1}{\omega_i} \int_0^t \ddot{u}(\tau) \sin \omega_i (t-\tau) d\tau \qquad \textbf{(2)}$$

characteristic shape functions:

$$X_i(x) = \frac{1}{\sqrt{l}} \left\{ cosh(\alpha_i x) - cos(\alpha_i x) - \frac{cosh(\alpha_i l) - cos(\alpha_i l)}{sinh(\alpha_i l) - sin(\alpha_i l)} \left[sinh(\alpha_i x) - sin(\alpha_i x) \right] \right\}$$

normal modes frequencies:

$$\omega_i = 2\pi \nu_i = \beta \alpha_i^2 \qquad cos(\alpha l) cosh(\alpha l) = 1 \qquad \beta = \sqrt{\frac{(EI)_\Sigma}{m_x}}$$

Approximated solution

Assumed deflection: $w(x,t) = q(t)f(x)$ **(1)**

$$f(x) = 16\left[\left(\frac{x}{l}\right)^4 - 2\left(\frac{x}{l}\right)^3 + \left(\frac{x}{l}\right)^2\right]$$ **(2)** or $f(\xi(x)) = 16\left(\xi^4 - 2\xi^3 + \xi^2\right)$ $\xi(x) = x/l$ **with** $f = 1$ **at** $\xi = 0{,}5$

Kinetic and potential energies:

$$T = \frac{1}{2}\int_0^l m_x \dot{w}^2\, dx = \frac{1}{2} m_e \dot{q}^2 \qquad m_e = m_x l \int_0^1 f^2 d\xi$$

$$U = \frac{1}{2}\int_0^l (EI)_\Sigma (w'')^2\, dx = \frac{1}{2} k_e q^2 \qquad k_e = \frac{(EI)_\Sigma}{l^3}\int_0^1 {f_{\xi\xi}}^2 d\xi \qquad (f'' = l^{-2} f_{\xi\xi})$$

Generalized force:

$$V = \int_0^l p(t)\, w\, dx = q\left(p(t)\, l \int_0^1 f\, d\xi\right) \qquad p(t) = -m_x \ddot{u}(t) = -m_x a_{max} \psi(t) \qquad |\psi(t)| \le 1$$

$$P_e(t) = \frac{\partial V}{\partial q} = p(t)\, l \int_0^1 f\, d\xi$$

Lagrange's equations of the second kind:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right) - \frac{\partial L}{\partial q} = P_e(t)$$ with Lagrangian $L = T - U$ ⇒

$$\ddot{q} + {\omega_e}^2 q = \frac{P_e(t)}{m_e}$$ with $${\omega_e}^2 = \frac{k_e}{m_e}$$

initial conditions: $q(0) = \dot{q}(0) = 0$

Duhamel's integral:

$$q(t) = \frac{1}{\omega_e}\int_0^t \frac{P_e(\tau)}{m_e} \sin[\omega_e (t - \tau)]\, d\tau$$

Simplified approach

Duhamel's integral: $$q(t)=\frac{1}{\omega_e}\int_0^t \frac{P_e(\tau)}{m_e}\sin[\omega_e(t-\tau)]d\tau = \frac{-m_x a_{max} l^4}{(EI)_\Sigma}\left(\frac{\int_0^1 f\,d\xi}{\int_0^1 f_{\xi\xi}{}^2 d\xi}\right)\omega_e\int_0^t \psi(t)\sin[\omega_e(t-\tau)]d\tau = w_{st,max}\bar{q}(t)$$

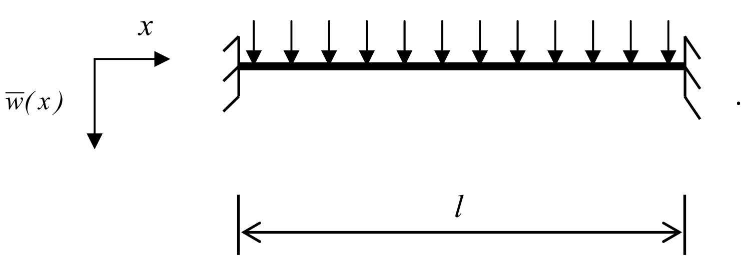
$$q(t)=w_{st,max}\ \bar{q}(t) \qquad w_{st,max}=-\frac{m_x a_{max} l^4}{384(EI)_\Sigma} \qquad \bar{q}(t)=\omega_e\int_0^t \psi(\tau)\sin[\omega_e(t-\tau)]d\tau$$

Bounded static formulation

Bounded deflection shape: $$|w(x,t)| = |f(x)q(t)| \le \bar{w}(x) = w_{st,max}\bar{q}_{max} f(x)$$

Equivalent static formulation: $(EI)_\Sigma \bar{w}^{IV}(x) = p_{eff}$ boundary conditions: $\bar{w}(0)=\bar{w}'(0)=\bar{w}(l)=\bar{w}'(l)=0$

$$p_{eff}=\bar{q}_{max} m_x a_{max}$$



effective static load

$$p_{eff} = -m_x a_{eff} = -m_x(\bar{q}_{max} a_{max}) \qquad \textbf{(1)}$$

with dynamic amplification factor

$$\bar{q}_{max} \ge \bar{q}(t) = \omega_e \int_0^t \psi(\tau)\sin[\omega_e(t-\tau)]\,d\tau \qquad \textbf{(2)}$$

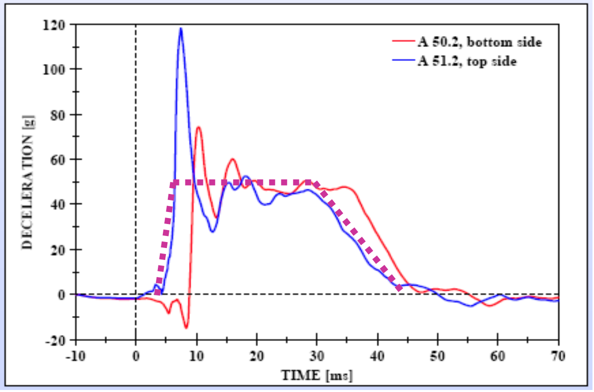
Dynamic amplification factor

CONSTOR V/TC Full-Scale Drop Test

9m horizontal drop (Sept.2004)

- the force transfer to the fuel rods is design dependent and not well-known:
  unyielding target → impact limiter → cask body → basket → fuel assembly (nozzles, spacer grid) → fuel rod
- the maximum decelerations of casks equipped with different types of impact limiters are in the range of 50 g up to 200 g,
- the impulse duration is about 20 ms to 30 ms,
- the form of impulse is different for different types of impact limiters,
- the maximum deceleration of the cask multiplied with the dynamic amplification factor can be used for the estimation of fuel rod response,
- for the octagonal impact limiter the impulse was nearly rectangular and long relatively to the natural period of the rod section:

  *the dynamic amplification factor would be nearly **2,0** in this case.*



Critical deformation state

Maximum bending moment and stress under distributed load $p = m_x a$ **:**

$M_{max} = (m_x a l^2)/12$ at $x = 0, l$

$\sigma_{max} = M_{max}/W_\Sigma$ with $W_\Sigma = I_\Sigma / r_a$ - section modulus of the fuel rod r_a - outer radius of the cladding

It will be assumed that the rod failure occurs at the <u>critical stress</u> in the cladding σ_f

critical deceleration :

$$a_f(\sigma_f) = 12 \frac{W_\Sigma}{m_x l^2} \sigma_f$$

critical deflection:

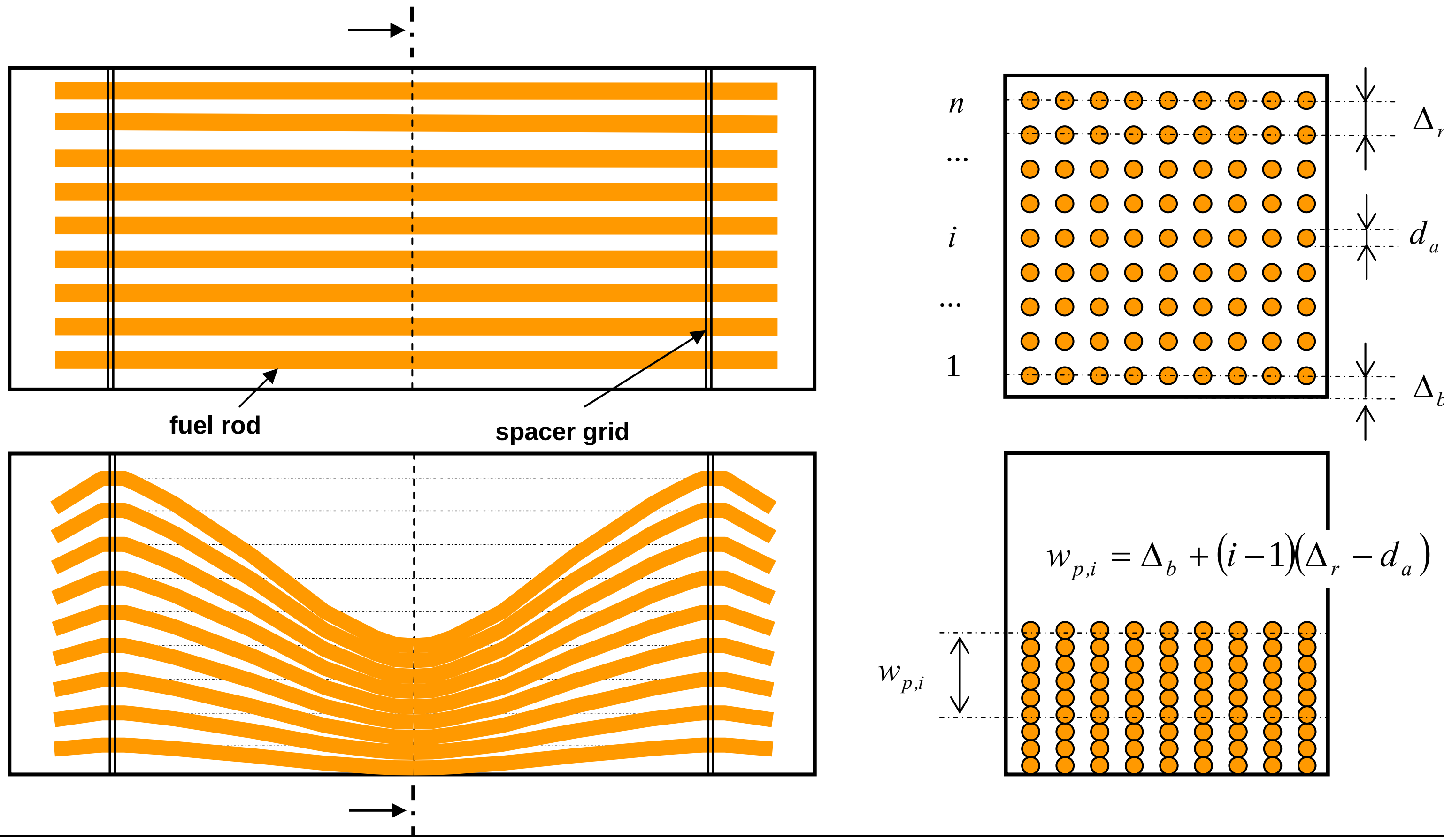
$$\overline{w}_f(\sigma_f) = \frac{p}{384} \frac{l^4}{(EI)_\Sigma} = \frac{l^2}{32 r_a E_C} \sigma_f$$

Maximum potential fuel rod deflections

Assumptions:

- packing-down in only one direction without lateral sliding,

- no deformations (collapse/buckling) of the intermediate spacer grids.



$$w_{p,i} = \Delta_b + (i-1)(\Delta_r - d_a)$$

Estimation of the potential fissile material release

- Comparison of the maximum possible deflections of the rods in the fuel assembly sections $w_{p,i}$ with the critical deflection $\overline{w}_f$:

- if $w_{p,i} < \overline{w}_f$ the bending without rupture of the cladding can be assumed,

- if $w_{p,i} \geq \overline{w}_f$ the breakage of the rod is possible.

- The potentially released fissile material mass is equal to

$$m_{SUM} = m_{UO2} n_f n_{FA} \quad \textbf{(1)}$$

with
m_{UO2} - mass released per fuel breakage
n_f - number of fuel rods breakage per fuel assembly
n_{FA} - number of fuel assemblies transported in the cask

- The fissile material release has to be considered if the condition

$$a_{eff} \geq a_f \quad \Rightarrow \quad (w_{st,max} q_{max} \geq w_f) \quad \textbf{(2)}$$

is valid for the maximum deceleration of the cask in horizontal drop .

The value m_{SUM} has to be consistent with the hypotheses in the criticality safety analysis.

Parameters and their experimental basis

- The assumed fuel rod response needs to be experimentally verified. The following questions are of particular importance :

- ***Which criteria should be used for the material rupture of high burn-up cladding under bending loading?***

- ***How much is the loading gap between the initiation of circumferential tearing to the complete rod breakage?***

- ***Does this gap decrease with the burn-up level?***

- ***How much is the fissile material mass released per fuel rod breakage?***

- The data from mechanical tests with cladding tensile specimens or with empty tube specimens give generally a limited benefit in this context.

- Bending tests with axial segments of irradiated fuelled rods are more useful for clarification of these questions but such experimental data are hardly available for public use at the moment .

Parameters and their experimental basis

- There are a wide scatter in the results of few known test campaigns, e.g. for the release of fissile material:

- Fuel Integrity Project (BNFL and TN-I)

  Static bending tests with 5 PWR and 3 BWR fuel rods specimens (approx. 50 GWd/tU)
  The mass of **10 g** per rod break is defined as bounded value.
  [P. C. Purcell and M. Dallongeville: RAMTRANS Vol.15, Nos.3-4, pp.163-164 (2004)]

- GNS, AREVA NP and TNU

  Impact bending tests with 3 PWR and 1 BWR fuel rods specimens (from 19 to 73,6 GWd/tU)
  The mass of **2 g** per rod break is defined as bounded value.
  [D. Papaioannou et al: Jahrestagung Kerntechnik, 12-14 Mai (2009)]

Conclusions

- Complexity of mechanical considerations for fuel assemblies should be governed by requirements of nuclear safety demonstration.
- A simplified methodology is generally preferred, which at the same time would suffice to support the assumptions in nuclear safety demonstration.
- Even for verification of a simplified mechanical analysis there are very limited experimental data.
- In view of wide scatter of spent fuel release measured in few known test campaigns and little data concerning the deformability of high burn-up fuel rods under accident specific bending loading, adequate safety factors have to be taken into account by using these test results.
- Particular test environments have to be considered in relation to the safety analysis case and the justification of data in the safety analysis report has to be based on complete test documentation.
- Further experimental investigations on this field are highly desirable.

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