# MECHANICAL SAFETY ANALYSIS FOR HIGH BURN-UP SPENT FUEL ASSEMBLIES UNDER ACCIDENT TRANSPORT CONDITIONS

**Viktor Ballheimer** **Frank Wille** **Bernhard Droste**

BAM Federal Institute for Materials Research and Testing, 12200 Berlin, Germany

## ABSTRACT

Transport packages for spent fuel have to meet the requirements concerning containment, shielding, and criticality as specified in the IAEA-Regulations for different transport conditions. Physical state of spent fuel and fuel rod cladding as well as geometric configuration of fuel assemblies are, among others, important inputs for the evaluation of correspondent package capabilities under these conditions. The kind, accuracy, and completeness of such information depend upon purpose of the specific problem. In this paper the mechanical behaviour of spent fuel assemblies under accident conditions of transport will be analysed with regard to assumptions to be used in the criticality safety analysis. In particular the potential rearrangement of the fissile content within the package cavity, including the amount of the fuel released from broken rods has to be properly considered in these assumptions. In view of the complexity of interactions between the fuel rods of each fuel assembly among themselves as well as between fuel assemblies, basket, and cask body or cask lid, the exact mechanical analysis of such phenomena under drop test conditions is nearly impossible. The application of sophisticated numerical models requests extensive experimental data for model verification, which are in general not available. The gaps in information concerning the material properties of cladding and pellets, especially for the high burn-up fuel, make the analysis more complicated additionally. In this context a simplified analytical methodology for conservative estimation of fuel rod failures and spent fuel release will be described. This methodology is based on experiences of BAM acting as responsible German authority within safety assessment of packages for transport of spent fuel.

## INTRODUCTION

Transport packages for spent fuel have to ensure criticality safety of the content under different transport conditions specified in the IAEA-Regulations. Criticality evaluation is based, among others, on the assumptions regarding the condition of fuel assemblies. However, in general, the exact description of the mechanical behaviour of spent fuel assemblies is not possible, especially under hypothetical accident conditions of transport simulated by drop tests. The impact loading of spent fuel assemblies depends on complex interactions between package components (impact limiters, cask body, basket, etc.). The response to this loading is specific not only for different fuel assembly designs but also for their operational or storage history. All these aspects significantly complicate the mechanical analysis. On the other hand if the subcriticality assessment shows sufficient safety margins under application of conservative assumptions concerning physical state and geometrical arrangement of spent fuel, the mechanical assessment part may be simplified only to the confirmation of these assumptions [1]. Although such an approach is used in actual licensing procedures, the experimental basis is still very limited, even for verification of a simplified mechanical analysis.

One of the effects to be considered in criticality safety evaluation for accident conditions of transport is the potential cladding failure followed by release of fissile material into the cask cavity [1]. This issue is especially important for high burn-up spent fuel (>50GWd/tU) because of degradation of the material properties under extended use (e.g. deterioration of cladding ductility), but only a few information concerning the experimental investigations for the high burn-up spent fuel under loading conditions specific for transport accidents is available for public [2, 3, 4]. Some principle aspects of estimation of spent fuel release are discussed in this paper on basis of a simplified mechanical analysis.

## GENERAL DESCRIPTION OF THE PROBLEM

Depending on the orientation of cask during drop tests, different components of cask, basket, and fuel assembly skeleton are involved in the transfer of impact loading to individual fuel rods. Specific deformations of fuel assemblies/fuel rods are induced. During horizontal (side) drop the fuel rods are primarily subjected to bending under transversal inertia loads so that the lattice pitch of the fuel assemblies tends to reduce. In a vertical (end) drop orientation the axial loading can lead to buckling of the fuel rods. A permanent expansion of the lattice, especially in the lower sections of fuel assemblies, can result from post-buckling bending deformations of the rods or from interaction with deforming nozzles. In other drop orientations combinations of deformation patterns described above can occur. In addition to bending loading, the rods are subjected to compressive (pinch) forces caused by rod-to-rod / rod-to-spacer grid interactions as well as by collisions of the fuel rods with basket or cask wall. Regarding potential rod failure, three modes are identified in a detailed study conducted by Sandia National Laboratories [5]: transverse tearing (Mode I) initiated under bending loading, extension of this mode to partial or complete rod breakage (Mode II), and longitudinal tearing (Mode III) due to pinch load.

The possibilities for a direct experimental investigation of the behaviour of the content within the cask under accident conditions are very limited. Cask drop tests with irradiated fuel assemblies can not be conducted. An exact mock-up of the fuel assemblies is nearly impossible as well. Rigidity and inertia characteristics of dummy fuel assemblies in drop tests are usually chosen to provide a conservative impact loading for the cask components. Moreover, it is difficult to instrument such test models for reliable quantity statements. Therefore a reasonable combination of computation methods and components tests, e.g. with fuel-in cladding tubes, is of decisive importance.

An example of numerical investigations is presented in [6]. A global finite-element model consisting of the cask body, basket, and fuel assemblies is used for preliminary calculations. One of the fuel assemblies (control assembly) is modelled in detail with beam elements for individual fuel rods. The impact forces and bending moments acting on the fuel rods of the control assembly are obtained from a global explicit analysis of cask drop. These loads are taken into account in the following static analysis with a refined model of a single fuel rod to define its potential failure configuration. A complex constitutive material law based on detailed material investigations was used for the irradiated Zircaloy cladding in this study. Obviously such sophisticated numerical approaches are necessary for a phenomenological understanding of the behaviour of fuel assemblies under accident conditions, especially regarding their failure mode and post-test geometry. However, it should be noted that due to a lack of adequate experimental verification the calculation results (already of the first global analysis step) contain a large number of hardly quantifiable uncertainties. The application of this methodology for practical cases seems to be problematical at the moment.

For mechanical analysis in the context of an approval procedure of a package design a simplified methodology is generally preferred, which at the same time allows an estimation of critical deformations and rod failure in agreement with assumptions in nuclear safety demonstration. A simplified approach for assessment of the amount of fissile material release is described in this paper. It is evident that rod breakage under bending (Mode II, [5]) 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 mass released 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 analyzed.

## MECHANICAL ANALYSIS OF SPENT FUEL RODS IN A SIDE DROP

In case of a side drop the fuel rods can be considered as continuous beams, supported at the position of spacer grids. During the drop event the deceleration forces of impact limiters are transmitted through the cask body, basket structure and spacer grids to the fuel rods. The fuel rods are thus exited dynamically through supports (spacer grids) motion, and not by external loading applied directly (kinematic excitation). Interactions between the fuel rods of a fuel assembly will be neglected first, and a free deflection of a single fuel rod in the plane of kinematic excitation will be considered. Due to nearly regular distribution of spacer grids along a fuel assembly (at least in the middle area) the analysis can be limited only to one rod inter-grid section clamped at both supports. The rod section will be assumed as straight uniform composite beam with elastic material behaviour. Significant physical properties are the mass per unit length $m_x$ and the flexural stiffness $(E\,I)_\Sigma$, both are taken to be constant along the span $l$. The effect of damping is neglected in the following analysis. This is possible because the maximum response to impulsive load (first peak value of deflection) is of interest, and not a continuous state of vibration. The flexural stiffness of the beam is given by $(E\,I)_\Sigma = E_c (I_c + E_p I_p / E_c) = E_c I_\Sigma$ with Young's modulus of elasticity $E$ and moment of inertia of the section $I$ for cladding (subscript $c$) and pellets (subscript $p$). The assumption of an elastic response of the beam seems to be justified owing to drastic decrease in cladding ductility of high burn-up fuel rods. Other degradations effects as for example oxidation of cladding and consequent reduction of its effective thickness should be taken into account. It is pertinent to note that the failure mode - breakage due to fuel rod bending - is not affected by radial hydrides. Questions concerning hydride reorientation are thus not relevant in this context.

<u>Dynamic lateral response of beam under displacement boundary conditions</u>

In case of kinematic excitation it is convenient to express the global displacement $w_g(x,t)$ of the beam's elastic axis from its original position as the sum of the displacements which would be induced by static application of the support motion, i.e. the so-called quasi-static displacement $w_s(x,t)$, plus the additional displacement $w(x,t)$ due to dynamic inertial force effects; thus

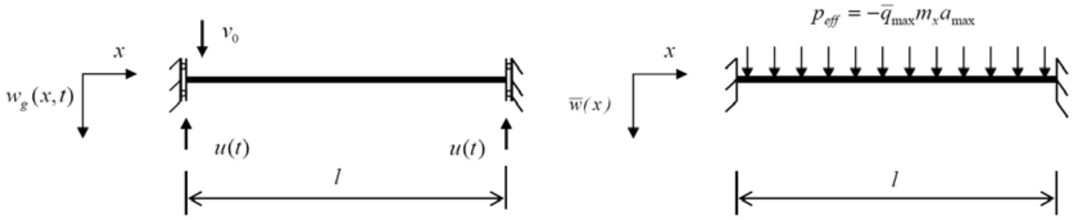
$$w_g(x,t) = w_s(x,t) + w(x,t) \tag{1}$$

In conformity with conditions of a side drop the beam is considered to have the initial velocity $v_0$ at time $t = 0$ (after free fall phase). From this time on, supports are decelerated. To keep derivation from becoming too involved, the equal, parallel directed decelerations of both supports without rotation are assumed, so the quasi-static component corresponds to rigid body displacement of the beam with the supports $w_s(x,t) = u(t)$ and function $w(x,t)$ describes the dynamic displacement of an arbitrary point of the beam about this rigid body motion (Fig. 1(a)). The equation of motion

$$(E\,I)_\Sigma w_g^{IV}(x,t) + m_x \ddot{w}_g(x,t) = 0 \tag{2}$$

must be solved so as to satisfy the initial and specified geometric boundary conditions given by

$$w_g(x,0)=0; \quad \dot{w}_g(x,0)=-v_0 \quad \text{and} \quad w_g(0,t)= w_g'(0,t)= 0\,;\; w_g(l,t)= w_g'(l,t)= 0 \qquad (3)$$




(a) (b)

**Figure 1. Beam subjected to support displacements (a) and equivalent static loading case (b)**

Substituting the expression (1) into equation (2) and transferring all terms associated with the quasi-static displacement and its derivatives to the right hand side lead to

$$(E\,J)_\Sigma\, w^{IV}(x,t)+m_x\ddot{w}(x,t)=-m_x\ddot{u}(t) \qquad (4)$$

in which the right member represents the effective distributed dynamic loading caused by the prescribed support excitations. The correspondent initial and boundary conditions are modified to

$$w(x,0)=\dot{w}(x,0)=0 \quad \text{and} \quad w(0,t)= w'(0,t)= 0\,;\; w(l,t)= w'(l,t)= 0 \qquad (5)$$

Bounded static formulation

The exact solution of the initial-boundary problem (4), (5) gives the deflection of the beam as the superposition of the contribution of an infinite number of normal modes of vibration. As already noted only the first peak value of deflection is of interest. It can be assumed that the first mode predominates in dynamic response. Reasonable accurate results can be obtained by considering only this mode. Alternatively, a deflected shape caused by load applied statically can be used as an approximation of the dynamic deflection curve. It is believed, that this procedure takes into account the contribution of higher modes and is more accurate. It should be noted that the results of these two approaches differ only slightly [7].

Thus the exact solution of the initial-boundary problem (4), (5) will be approximated by

$$w(x,t)=q(t)\,f(x) \qquad (6)$$

in which the function

$$f(x)=16\left[\left(\frac{x}{l}\right)^4-2\left(\frac{x}{l}\right)^3+\left(\frac{x}{l}\right)^2\right] \quad \text{or} \quad f(\xi(x))=16\left(\xi^4-2\xi^3+\xi^2\right) \quad \text{with} \quad \xi(x)=x/l \qquad (7)$$

represents the static deflected shape of clamped beam under uniform distributed load. For convenience $f=1$ at $\xi=0.5$ is chosen. The kinetic and potential energies of the beam are given by

$$T=\frac{1}{2}\int_0^l m_x\dot{w}^2\,dx=\frac{1}{2}m_e\dot{q}^2 \qquad \text{with} \quad m_e=m_x l\int_0^1 f^2 d\xi \qquad (8)$$

and

$$U=\frac{1}{2}\int_0^l (E\,I)_\Sigma (w'')^2\,dx=\frac{1}{2}k_e q^2 \quad \text{with} \quad k_e=\frac{(E\,I)_\Sigma}{l^3}\int_0^1 f_{\xi\xi}{}^2 d\xi\,, \quad (f''=l^{-2}f_{\xi\xi}) \qquad (9)$$

From the expression $V=\int_0^l p(t)\,w\,dx=q\left(p(t)\,l\int_0^1 f\,d\xi\right)$ for the work done by the external load

$$p(t)=-m_x\ddot{u}(t)=-m_x a_{\max}\psi(t)\,, \quad |\psi(t)|\le 1 \qquad (10)$$

the generalized force can be obtained

$$P_e(t)=\frac{\partial V}{\partial q}=p(t)l\int_0^1 f\,d\xi \tag{11}$$

On basis of Lagrange's equation $\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right)-\frac{\partial L}{\partial q}=P_e(t)$, with the Lagrangian $L=T-U$,

the equation for generalized coordinates $q(t)$ can be derived

$$\ddot{q}+\omega_e{}^2 q=\frac{P_e(t)}{m_e} \qquad \text{with} \qquad \omega_e{}^2=\frac{k_e}{m_e} \tag{12}$$

The solution of equation (12) with initial condition $q(0)=\dot{q}(0)=0$ is expressed by Dyhamel's integral

$$q(t)=\frac{1}{\omega_e}\int_0^t \frac{P_e(\tau)}{m_e}\sin[\omega_e(t-\tau)]d\tau \tag{13}$$

Considering the expressions for $m_e$ , $k_e$, $P_e$, and $f(\xi)$ the solution (13) can be transformed to

$$q(t)=\frac{-m_x a_{\max} l^4}{(EI)_\Sigma}\left(\frac{\int_0^1 f\,d\xi}{\int_0^1 f_{\xi\xi}{}^2 d\xi}\right)\omega_e\int_0^t \psi(t)\sin[\omega_e(t-\tau)]d\tau = w_{st,\max}\overline{q}(t) \tag{14}$$

where $w_{st,\max}=-\frac{m_x a_{\max} l^4}{384(EI)_\Sigma}$ is the maximum static deflection and

$$\overline{q}(t)=\omega_e\int_0^t \psi(\tau)\sin[\omega_e(t-\tau)]d\tau \tag{15}$$

On basis of equation (6) the bounded deflection shape of the beam can be obtained

$$|w(x,t)|=|f(x)q(t)|\le \overline{w}(x)=w_{st,\max}\overline{q}_{\max}f(x) \tag{16}$$

where the maximum of function (15) is defined as dynamic amplification factor $\overline{q}_{\max}$.

Obviously the bounded deflection of the beam (Fig. 1(b)) is equal to the solution of boundary value problem

$$(E\,I)_\Sigma \overline{w}^{IV}(x)=p_{eff}\,, \qquad \overline{w}(0)=\overline{w}'(0)=\overline{w}(l)=\overline{w}'(l)=0 \tag{17}$$

for the effective static load of

$$p_{eff}=-m_x a_{eff}=-m_x(\overline{q}_{\max}a_{\max}) \tag{18}$$

## ESTIMATION OF POTENTIAL FISSILE MATERIAL RELEASE

The maximum bending moments in a claimed beam under assumed uniform inertia load $p=m_x a$ occur at the claimed ends and are equal to $M_{\max}=(m_x a\,l^2)/12$. The maximum bending stress can be obtained from $\sigma_{\max}=M_{\max}/W_\Sigma$ where $W_\Sigma=I_\Sigma/r_a$ is the section modulus of the composite beam ($r_a$=outer radius). Assuming that $\sigma_f$ is the critical stress in the cladding, which leads to complete failure of the rod, the correspondent critical deceleration value (19) and the correspondent critical deflection (20) can be calculated:

$$a_f(\sigma_f) = 12\frac{W_\Sigma}{m_x\, l^2}\sigma_f \tag{19}$$

$$\overline{w}_f(\sigma_f) = \frac{p}{384}\frac{l^4}{(E\,I)_\Sigma} = \frac{l^2}{32\, r_a\, E_C}\sigma_f \tag{20}$$

Free deflection of a fuel rod is limited by other rods of the fuel assembly and by cask or basket walls. The worst geometrical configuration has to be considered for a conservative estimation of the potential fissile material release under accident conditions. For the horizontal drop the packing down of fuel rods in one direction is typical. The maximum available bending deflections of rods depend on their position in the rod array. The determination of the available deflections is illustrated in Figure 2 for an example of a "regular" compaction of the rods. Other configurations, e.g. with sliding of some rods in the gaps between the columns are possible as well and should be analysed in each specific case.

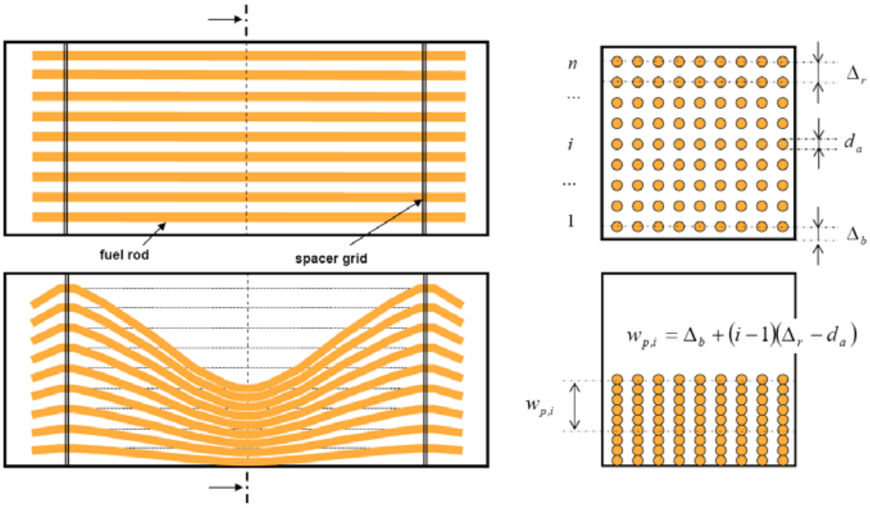



**Figure 2. Estimation of maximum potential rod deflection**

Assume that $m_{UO2}$ is the mass of fissile material released per fuel rod breakage. The number of potential fuel rods breakage per fuel assembly $n_f$ can be estimated by comparison of the maximum possible deflections in the inter-grid sections of fuel assembly $w_{p,i}$ with the critical deflection $\overline{w}_f$ (20):

- if $w_{p,i} < \overline{w}_f$ the rods in row $i$ will bend without rupture of the cladding,
- if $w_{p,i} \geq \overline{w}_f$ the breakage of the rods has to be considered.

The amount of potentially released fissile material is then equal to $m_{SUM} = m_{UO2} n_f n_{FA}$ (with $n_{FA}$ as number of fuel assemblies transported in the cask).

A comparison between the effective deceleration $a_{eff} = -\overline{q}_{\max} a_{\max}$ expected for the fuel rods in horizontal drop of the cask and the critical value (19) determines whether such a release scenario could occur in a hypothetical accident. The fissile material release $m_{SUM}$ has to be considered if the condition $|a_{eff}| \geq a_f$ is reached. It should be emphasized that the dynamic amplification factor is involved in the equation (18) so that the effective static load is, in general, a function of deceleration history $\psi(t)$ and fuel rod dynamic characteristics represented by natural frequency of equivalent system $\omega_e$. The critical deceleration (19) depends on mechanical characteristics of

cladding and fuel inside ($W_\Sigma$). By contrast, the critical deflection (20) depends only on cladding parameters.
The cask deceleration can be measured by drop test or calculated by means of an appropriate numerical model. The magnitude and form of deceleration-time curve are primarily depending on the impact limiter system of the cask. By BAM experience, a range of maximum decelerations between 50 g and 200 g is expected by side drop of transport casks for spent fuel. The impact impulse duration is about 20 ms to 30 ms. If only an approximation of effective loading is sufficient for the analysis, the deceleration characteristic can be idealized by simple mathematical expression (e.g. as sine wave, rectangular or triangular impulse). The stiffness of basket as well as clearances between fuel assemblies, basket, and cask body influence the transfer of cask deceleration to the fuel rods. Such phenomena should be also addressed in each specific case. Some aspects of this complex problem are discussed in [8].

## PARAMETERS AND THEIR EXPERIMENTAL BASIS, OPEN QUESTIONS

Based on the methodology outlined above, the potential release of fissile material under accident conditions of transport can be estimated and used as input in nuclear safety demonstration. However the assumed fuel rod response needs to be experimentally verified. The following questions are of particular importance:
- Which criteria should be used for rupture of high burn-up cladding under bending loading?
- How much is the loading gap from the initiation of circumferential tearing to the complete rod breakage (gap between failure modes I and II, [5])? Does this gap decrease with the burn-up level?
- How much is the fissile material mass released per fuel rod breakage?

It should be noted that the data from mechanical tests with cladding tensile specimens (longitudinal/transverse) or with empty tube specimens give generally a limited benefit in this context because of different behaviour of fuel rods as a composite structure of cladding and spent fuel. Bending tests with axial segments of irradiated fuelled rods are more useful for clarification of these questions but such experimental data are hardly available at the moment for public use.
One of few examples is the fuel integrity project (FIP) of BNFL and TNI, in which two series of static bending tests with irradiated fuel rod specimens (5 PWR and 3 BWR) were carried out. The specimens with approximately 50 GWd/tU burn-up were loaded at slow deformation rate up to a complete break. The test configuration and qualitative results are described in [2] and [3]. Some quantitative test data (e.g. force-deflection curve) are presented in connection with numerical analyses as well [3]. Release of fissile material is not discussed in detail. The mass of 10 g per rod break is defined in [2] as a bounded value for the released amounts measured in both test series.
The bending tests with irradiated rod segments having burn-up from 19 GWd/tU to 73.6 GWd/tU are described in [4]. Fuel rod specimens (3 PWR and 1 BWR) were claimed at both ends and loaded laterally by a free falling hammer. The specimens with the lowest burn-up showed 3 deep cracks at the middle and at the ends. The other specimens broke completely at these positions. The mass of 2 g is defined as bounded value for release of irradiated fuel per rod break.
Worthy of mention is also the GRS project [9], in which some methodical investigations concerning the bending loading of fuel rods were conducted, but unfortunately this project was not extended to the tests with irradiated rod segments.

## CONCLUSIONS

Physical state of spent fuel and fuel rod cladding as well as geometric configuration of fuel assemblies are, among others, important inputs for the criticality safety assessment under accident conditions of transport. Since an exact determination of geometric changes in fuel assemblies and fuel release from broken fuel rods is highly questionable, the extent of mechanical considerations should be governed by requirements of nuclear safety analysis.

Some principle aspects of simplified mechanical approaches for estimation of fissile material release were discussed in this paper by the example of fuel rods under bending loading typical for a side drop orientation. The critical load causing a breakage of an individual fuel rod in the inter-grid section and the corresponding rod deflection have to be defined at first. The comparison of these values with an effective loading expected under accident conditions and with free deflections available in fuel assembly lattice, leads finally to the conclusion about potential rod failure and consequent fuel release. An appropriate dynamic amplification factor has to be taken into account for the correct estimation of the effective inertia loading of fuel rods.

Even for verification of such a simplified mechanical analysis, there are very limited experimental data. In view of wide scatter of released mass of fissile material measured in few known test campaigns, in which the accident specific bending loading was simulated, as well as little data concerning the deformability of high burn-up fuel rods under such loading, adequate safety factors have to be taken into account by using these test results. The different test environments have to be considered in relation to the safety analysis case and the justification of data for a competent authority has to be based on complete test documentation. It is apparent that further experimental investigations on this field are highly desirable.

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