

Package Design Assessment Aspects of Gaps between Content and Lid

Frank Wille
Thomas Quercetti

Viktor Ballheimer
Jens Sterthaus

Bundesanstalt für Materialforschung und -prüfung (BAM)
Unter den Eichen 87
12205 Berlin, Germany

Abstract

Type B(U) packages for the transport of radioactive material have to withstand accident conditions of transport defined in the regulations of the IAEA International Atomic Energy Agency in form of different mechanical (drop) tests with a subsequent thermal test. According to the regulatory requirements the orientation of the package in drop tests shall be such to cause the most damaged state in the components performing the safety functions.

For the package lid system a 9-m drop onto the unyielding target with lid side downwards is often the most damaging orientation. The impact loads acting on the lid in this orientation result mainly from interaction between lid and internal content. In case of a movable content its impact onto the inner side of the lid can cause additional load peaks on the lid and the lid bolts. The intensity of the internal collision depends on the position of content relating to lid at the time of package first contact with target. Due to physical limitations an axial gap, which could be set in “pre-drop” configuration of package or which could spontaneously appear during the drop test, usually does not cover the maximum size possible in specific package design. In this context, the combination of drop tests with post-test analysis can be helpful to better estimate the effect of internal impact.

The paper summarized some aspects of this issue based on the BAM experience in the design assessment of Type B(U) transport packages. Additionally the paper shall support applicants in German approval procedures to reduce rounds of questions and ensure delivery of reliable safety case documents to the authorities. International discussions of this issue at the IAEA and a joint proposal by France and Germany to improve Advisory Material text will be introduced.

Introduction and problem description

Type B(U) packages for the transport of radioactive material commonly have a thick-walled body with an inner cavity in which the radioactive material and its support structures (e.g. basket for spent fuel assemblies) are enclosed. The containment system is completed by bolted lids with metal or elastomer seals. To fulfil the regulatory requirements concerning activity release [1], structural integrity and tightness of the lid system have to be ensured under transport conditions. According to the IAEA Regulations [1] accident conditions of transport are covered by cumulative effects of sequences including mechanical drop tests and a fire test. The drop orientations of the package, which cause the most deterioration of its safety functions, are decisive for the design assessment under test conditions. These orientations can be different for different components of the package.

For the lid system a 9 m drop onto an unyielding target with lid side downwards is often the most damaging case. Drop tests performed by BAM (Federal Institute for Materials Research and

Testing) have shown that in this orientation the impact loadings of the lid and the lid bolts are very sensitive to the mode of interaction between the lid and the content of the package. In this paper the term “content” is used for all components and materials enclosed in the package cavity.

The lid/content interaction is especially intense in case of a movable content. Technological gaps between content and lid or package walls exist because of geometrical dimensions of the content or due to thermal reasons. If the content is not fixed, its relative movement in the cavity can affect the dynamic behavior of the package and extremely raise the impact loads on the lid system. Obviously the loads acting on the components of the content in these internal collisions can be significant as well. However this aspect is not the subject of this paper.

The reasons for the occurrence of the internal impacts in drop tests with packages having movable contents are discussed in preceding papers by BAM [2-5]. Experimental results from drop tests performed by BAM as well as associated analysis results are presented in these publications.

Mention should be made of some other papers on this issue [6-9]. Two simplified approaches considering the interaction between the cask and its content are applied in [6, 7]. The main objective of the parameter study conducted in [6] is the examination of relationship between cask and content accelerations in drop events. Among other factors, the gaps in the cask cavity were varied in this study. In [7] a simple lumped mass-spring model was used to estimate the effect of axial gap on the impact response of a cask lid. Paper [8] presents the finite element (FE) calculations for a simplified transport package with gaps between content and lid. The paper focuses on the dynamic analysis of 9 m vertical drop and how loading conditions for a subsequent fuel assembly analysis can be extracted. In paper [9] the behaviour of two types of movable content during a 9 m free fall and their effect on the loading of the lid were numerically investigated. In the first FE model the content is simulated as one body whereas in the other it is divided into the basket and the simplified fuel assemblies.

All these studies show that the size of the axial gap between the content and the lid at the moment of package impact onto the target is the governing parameter for the impact loads on the lid system. Nevertheless, it has not been definitely clarified how these effects and especially which gap size have to be considered in the design assessment. The IAEA Transport Regulations SSR-6 [1] and accompanied IAEA Advisory Material SSG-26 [10] do not give clear recommendation on this issue at the moment. In this paper the BAM point of view and the current international discussions at IAEA level will be presented.

Internal impacts during drop tests

The appearance of the axial gap during the free fall phase of a vertical drop test is investigated and discussed in former publications by BAM [2-4]. The main causes of this phenomenon are summarized below.

In the initial position of the test orientation with package lid side downwards the content is resting on the package lid. Before release of the package its components including the content are deformed due to gravitation. After release the static equilibrium state is disrupted and the deformation energy stored in the structure is setting free. As long as the lid and the content remain in contact, they exert equal and opposite forces on each other, so that the packaging and the content have slightly different speeds at the time of contact separation.

This initial speed difference Δv leads to a relative movement of the packaging and the content in the free fall phase, and finally to a gap $h = \Delta v \times t_f$ between the content and the lid at the moment t_f of package (impact limiter) impact onto the unyielding target. While the packaging is already being decelerated by the impact limiter, the content is still in free fall and collides then with the lid with a time delay.

As noted above the gap sizes between the content and the lid, which can potentially appear in each particular 9 m drop test, depend on the deformation energy retained in the structure before release. Furthermore, many additional factors, such as the actual positioning of the contents on the lid in the

start configuration, friction or adhesion effects are of importance. These factors are of a rather random nature and are difficult to adjust and to reproduce in the drop tests especially with heavy packages. The differences in test results of full scale and reduced scale models of the package discussed in [5] can support this conclusion. In this test series the delayed internal impact was observed only in the prototype model and did not appear with a comparable intensity in the reduced scale model test.

Among other things this example clearly demonstrates that a decision on a strategy of mechanical design assessment under accident conditions of transport (drop tests, calculations or combination of both methods) should be based on a thorough analysis of the prerequisites, evolution and potential consequences of the internal impact effects in order to take proper account of the most damaging load combinations for the package as required by the regulations.

Theoretical considerations

Quasi-static calculation models are often used for the mechanical assessment of the package lid system. As a rule the content is represented by inertial force derived from the maximum rigid body deceleration which, in its turn, is obtained experimentally or by calculation. The question whether the real content/lid interaction is covered by this assumption is infrequently addressed in the package design safety reports. Such analysis is challenging due to the large number of parameters of the mechanical system involved, so that an unambiguous general solution is difficult and in many cases impossible to obtain. The gap size, for instance, determines the point in time at which the internal impact occurs and therefore the velocities of the content and the packaging (lid) at this moment as initial conditions for the impact problem. But the intensity of the impact interaction and the loads on the lid system essentially depend on mechanical properties of the collision partners as well.

The interaction between components of the package can be roughly illustrated by a multi-degrees-of-freedom (MDOF) system shown in Fig. 1 (case A). The masses m_2 and m_3 can be interpreted as masses of the lid and the content, the mass m_1 relates to the remaining components of the package. $F(x_1(t))$, $f_2(x_2(t) - x_1(t))$ and $f_3(x_3(t) - x_2(t))$ represent the reaction force of the impact limiter, the composite stiffness characteristic of the bolted lid and the reaction force of the content.

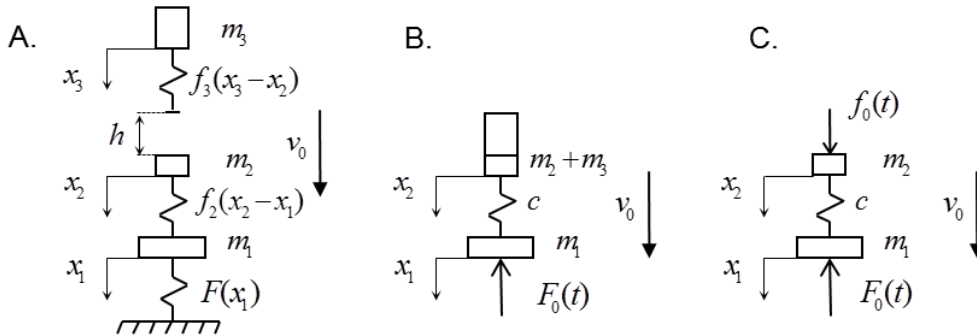


Figure 1: Simplified MDOF models

The differential equations of motion after the MDOF system impacts onto the target and the correspondent initial conditions have the following form

$$\begin{cases} m_3 \ddot{x}_3 + f_3(x_3 - x_2) = 0 \\ m_2 \ddot{x}_2 + f_2(x_2 - x_1) - f_3(x_3 - x_2) = 0 \\ m_1 \ddot{x}_1 + F(x_1) - f_2(x_2 - x_1) = 0 \end{cases} \quad t_0 = 0: \begin{cases} x_{1,0} = x_{2,0} = 0, x_{3,0} = -h, \\ \dot{x}_{1,0} = \dot{x}_{2,0} = \dot{x}_{3,0} = v_0 \end{cases} \quad (1)$$

where v_0 is the initial velocity (resulting from the free fall) and h is the initial distance between the masses m_2 and m_3 (from the content to the inner side of the primary lid). If the masses m_2 and m_3 are not in contact we have to set $f_3 = 0$. For simplicity's sake, the damping forces are not considered in (1).

The system (1) has an analytical solution only for some force characteristics. In practical cases numerical methods can be used if the forces are specified beforehand. We consider here only two simple examples of the common system (1) (Fig. 1, cases B and C) to demonstrate dependence of the spring reaction f_2 ("lid response") on the interaction modes between masses m_2 and m_3 . In both cases a linear characteristic with a coefficient c for the spring f_2 is assumed. The impact limiter is described by the constant force $F(x_1(t)) = F_0 = (m_1 + m_2 + m_3) \cdot a_0$ having conservatively the same value for the impact phase and rebound phase.

In the case B m_3 is rigidly connected with m_2 :

$$\begin{cases} (m_2 + m_3)\ddot{x}_2 + c \cdot (x_2 - x_1) = 0 \\ m_1\ddot{x}_1 + F_0 - c \cdot (x_2 - x_1) = 0 \end{cases} \quad t_0 = 0 : x_{1,0} = x_{2,0} = 0, \dot{x}_{1,0} = \dot{x}_{2,0} = v_0 \quad (2)$$

The loading of the "lid" spring is indicated by its deformation $y = x_2 - x_1$. From (2)

$$y = \frac{1}{p_\Sigma^2} \frac{F_0}{m_1} (1 - \cos(p_\Sigma t)) = y_{st} (1 - \cos(p_\Sigma t)) \quad \text{with} \quad p_\Sigma^2 = \frac{c \cdot (m_1 + m_2 + m_3)}{m_1 \cdot (m_2 + m_3)}$$

Therefore the maximum spring deformation in the loading case B is

$$y_{B,\max} = 2y_{st} \quad \text{with static displacement} \quad y_{st} = \frac{(m_2 + m_3)}{c} a_0 \quad (3)$$

The dynamic load factor of 2.0 reflects the response of the system to the rectangular force characteristic F_0 .

In the case C the mass m_3 collides with the mass m_2 at the time $t = t_*$ after beginning the "global" deceleration process. The interaction force between the masses m_3 and m_2 will be assumed as a function of the relative contact velocity $\Delta v_* = \dot{x}_3(t_*) - \dot{x}_2(t_*)$

$$f_3(x_3(t) - x_2(t)) = f_0(t) = \begin{cases} 0, & t < t_* \\ \bar{f}_0(\Delta v_*), & t \geq t_* \end{cases} \quad (4)$$

The equations of motion are

$$\begin{cases} m_2\ddot{x}_2 + c \cdot (x_2 - x_1) - f_0(t) = 0 \\ m_1\ddot{x}_1 + F_0 - c \cdot (x_2 - x_1) = 0 \end{cases} \quad t_0 = 0 : x_{1,0} = x_{2,0} = 0, \dot{x}_{1,0} = \dot{x}_{2,0} = v_0 \quad (5)$$

and the solution for the spring deformation $y = x_2 - x_1$ in this case is

$$y = \begin{cases} \frac{1}{p^2} \frac{F_0}{m_1} (1 - \cos[pt]) & t < t_* \\ \frac{1}{p^2} \left(\frac{F_0}{m_1} + \frac{\bar{f}_0}{m_2} \right) (1 - \cos[p(t - t_*)]) + y_* \cos[p(t - t_*)] + \frac{\dot{y}_*}{p} \sin[p(t - t_*)], & t \geq t_* \end{cases} \quad (6)$$

with $p^2 = \frac{c \cdot (m_1 + m_2)}{m_1 \cdot m_2}$.

In order to avoid unnecessary complexity in this qualitative analysis the deformation of the spring c and the relative velocity of the mass m_2 at the time $t = t_*$ will be neglected:

$$y_* = \frac{1}{p^2} \frac{F_0}{m_1} (1 - \cos[pt_*]) \approx 0, \quad \dot{y}_* = \frac{1}{p} \frac{F_0}{m_1} \sin[pt_*] \approx 0.$$

Then the time point of the impact between the mass m_3 and m_2 as well as their relative contact velocity can be defined against the initial gap size from the equation $x_3(t_*) - x_2(t_*) = h = at_*^2/2$ as

$$t_* \approx \sqrt{2h/a} \quad \text{and} \quad \Delta v_* = \dot{x}_3(t) - \dot{x}_2(t) \approx \sqrt{2ah} \quad (7)$$

in which $a = \frac{F_0}{(m_1 + m_2)} = \frac{(m_1 + m_2 + m_3)}{(m_1 + m_2)} a_0$.

The maximum deformation of the spring in the loading case C can be obtained from the equation (6) as

$$y_{C,\max} \approx 2 \frac{1}{p^2} \left(\frac{F_0}{m_1} + \frac{\bar{f}_0}{m_2} \right). \quad (8)$$

When this result is compared with that of case B (3), it is apparent that the condition $y_{C,\max} \leq y_{B,\max} = 2y_{st}$ will be fulfilled if $\bar{f}_0 \leq m_3 a_0 = \frac{m_3}{m_1 + m_2 + m_3} F_0$. Only for the impact forces under this value, the loading case B with rigidly connected masses m_2 and m_3 will cause higher spring deformations (forces) than the impact interaction in case C. Knowing the impact force dependence of the gap size (or of the relative contact velocity) the corresponding limiting gap h_l can be derived from this condition. This is illustrated schematically in Fig. 2 where the interaction force is assumed as a linear function of the contact velocity $\bar{f}_0 = \alpha + \beta \cdot \Delta v_* \approx \alpha + \beta \cdot \sqrt{2ah}$ with the constants α and β representing properties of the content (geometrical and physical).

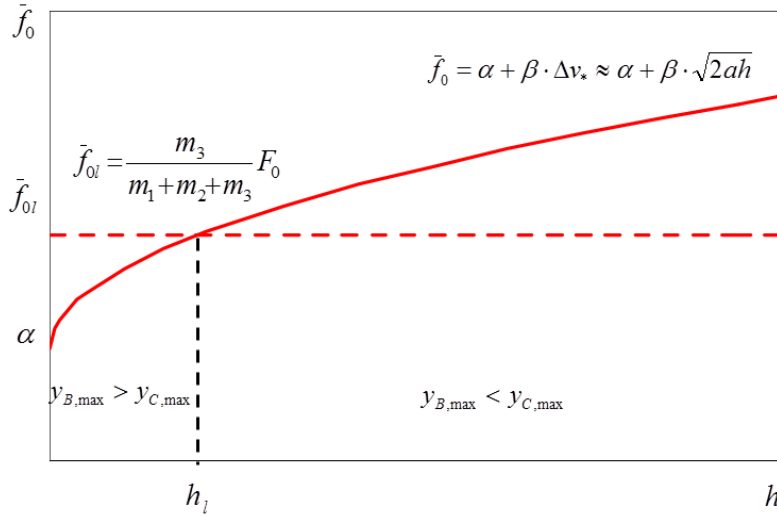


Figure 2: Relation between interaction force and gap size

This qualitative analysis demonstrates the limitations of the quasi-static models for the mechanical assessment of the lid system: the approach based on the maximum rigid-body deceleration of the package is applicable only for certain combinations of its parameters, which define the relative position of the curves in Fig. 2 and the existence of a limiting gap value h_l . For the given mass ratios m_1/m_3 and m_2/m_3 the domain of applicability of the quasi-static approximation depends on the correlation between the force characteristics of the impact limiter and the content. The domain of applicability expands with increasing stiffness of the impact limiter and decreasing stiffness of the content. This common nearly obvious conclusion can be useful in the design process.

Moreover, the dynamic load factors for possible dynamic amplifications in the vibration response of the lid system have to be included in the load assumptions of the quasi-static model. In general, this factor is a function of the rise time, duration, and shape of the load as well as of the natural period of the structure. In the example presented, the dynamic load factor of 2.0 is applied on both the

impact limiter and content/lid interaction forces due to their assumed instantaneous rise and sufficiently long duration. For other load-time functions the specific considerations would be necessary.

A rough quantitative estimation of the internal impact effect can be also made by consideration of the impulse of the interaction force assuming that this force is infinite and acts during an infinitesimal time interval. This means, that any ordinary finite forces (e.g. of the impact limiter) are negligible in comparison with the internal impact force. The amplification factor derived e.g. in [7] for the lid system in response to internal collision is based on such argumentation with an additional assumption about the completely plastic character of this interaction.

Analogical relationship can be obtained also from the second equation (6) after its corresponding transformations. It should be pointed out, that such estimations are inevitably uncertain and often too conservative owing to a lot of essential simplifications regarding the internal collision made to obtain an analytical result for a more or less common case.

Analysis example

In order to gain a better understanding of the effects observed in the 9 m vertical drop test with the full scale package performed by BAM, an analytical MDOF model was developed. The model was built of lumped masses and springs, which represent the inertia and deformation properties of the main components of the cask involved in the drop event. The detailed description of the model and comparison between experimental and analytical results can be found in paper [4]. The calculation results correlate well with the experimental measured decelerations and strains before and during the internal impact phase (Fig. 3).

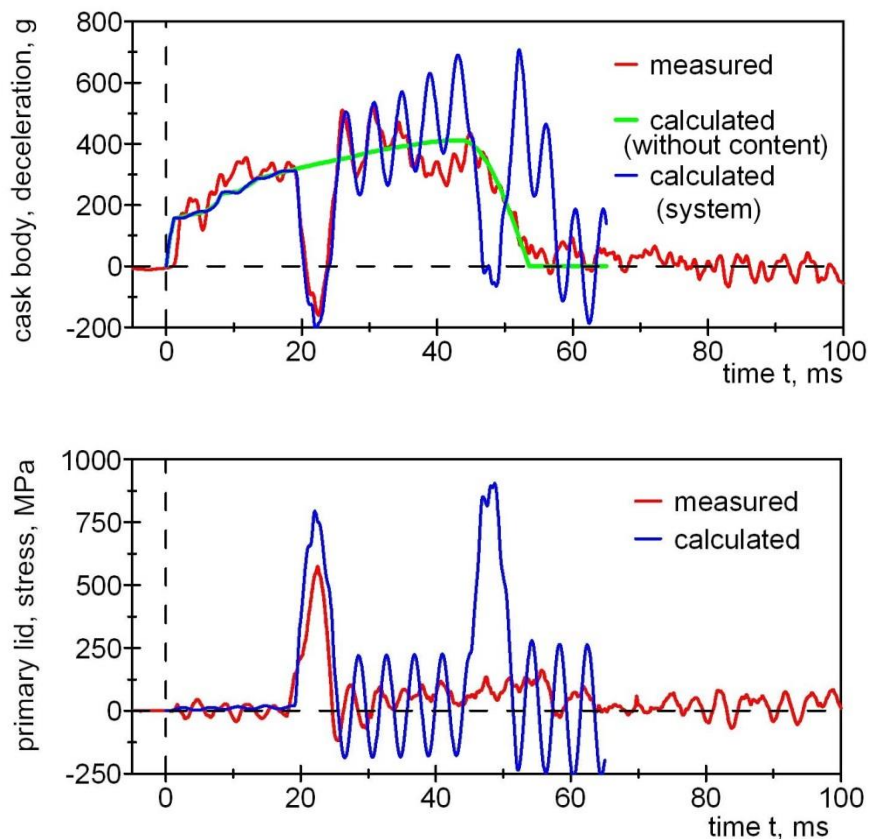


Figure 3: Comparison of experimental and analysis data

It was noted in [4] that after the first internal impact during the drop test, the components of content (basket profiles and the dummy fuel assemblies) moved separately from each other, and therefore, the effects of following collisions of these parts with the primary lid were smoothed. By contrast, in

the numerical simulation, both the basket and the dummy content are assumed to move as units after the first internal impact as well, and so the second internal impact at time t of ~ 46 ms can be clearly seen.

With this model the influence of the gap size onto the loading of the lid can be considered now. The deflection of the lid is used for comparison in this example. Due to the design features of the content discussed above, the repeated collisions between the content and the lid were not intensive in the drop test and the calculation model significantly overestimates these effects. Therefore it makes sense to compare only the deflections after the first impact.

Fig. 4 shows the results of this comparative analysis. The dynamic calculation for the content rigidly connected with the lid is used as basis configuration. In relation to the basic lid deflection the result for a gap size of 35 mm, corresponding to the drop test [4], has an amplification factor of 4.2. The consideration of the maximum possible gap in package cavity of 54 mm lead to an additional increase in the lid deflection of 40% and the amplification factor reaches 5.3. The relationship between the gap size and amplification factor for lid deflection can be approximately defined as $k = 1.0 + 0.55\sqrt{h}$.

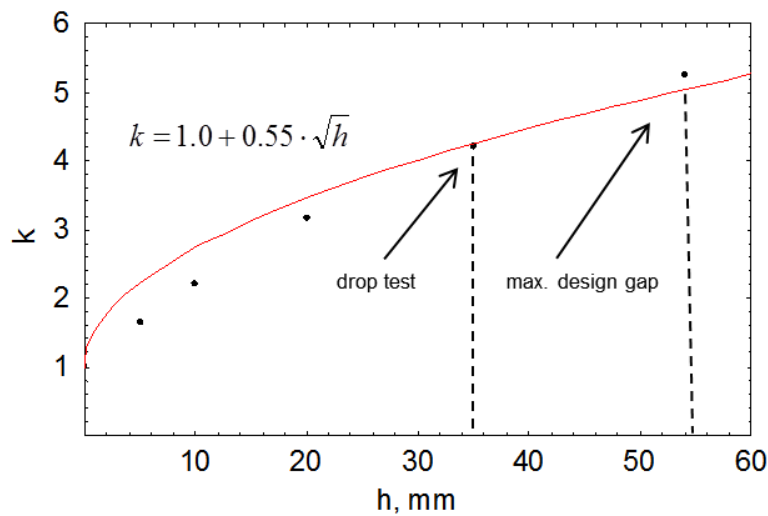


Figure 4: Relation between gap size and amplification factor for lid deflection

Because of a non-linear load characteristic of the bolted connection the last relation cannot be directly applied to the loading of the lid bolts. Separate investigations are needed for this, but the above consideration would suffice to exemplarily illustrate the axial gap effects in case of real package design.

Regulatory requirements

The examples demonstrate the governing character of the axial gap size for the lid loads due to an internal content/lid collision. However, as evidenced by drop tests (e.g. [5]) the gap occurring in a more or less random way during the phase of the free fall is usually not equal to the maximum design gap. The principal question is: Which gap size should be taken into account in the mechanical assessment of the lid system? Of course, this question pertains equally to both experimental and computational approaches in the safety analysis.

The current International Transport Regulations SSR-6 [1] with the corresponding Advisory Material SSG-26 [10] does not include any explicit requirements concerning this issue. Therefore, it is not surprising that two different interpretations of the regulatory statements are under discussion. The first one proceeds from a real transport situation. During package loading with radioactive content the packaging is normally located upright. After assembly of the lid the distance between the lid inner side and the content determines the maximum possible design gap (if the thermal elongation after assembly is ignored). This gap will be retained during the transport independent of

package orientation on the conveyance (vertical or horizontal). The loads on the components of the package in hypothetical accidents would be affected by this gap. This maximum gap size could therefore be a condition for obtaining the maximum damage in accordance with the requirements of the Regulations SSR-6 [1] para 727.

On the other hand it has been argued that the test sequences, which include also the 9 m vertical drop with content in the initial state resting on the lid, are already defined in regulations as covering for hypothetical accidents. From this standpoint the consideration of any other gaps, than those that can be achieved under physical laws in drop tests, is not necessary and such consideration is even inconsistent with the regulations. Only in particular cases of packages with content adhering or being attached to bottom the maximum gap have to be taken into account in drop tests.

Apparently, the wording of the regulations allows both of these interpretations. Physically, both approaches can be justified as well.

However, BAM follows the point of view that any possible interactions between the content and the lid system are to be considered in the safety analysis. In our opinion this is in a general agreement with the following explanations in the IAEA Advisory Material SSG-26 [10], para 701.3 and 701.5:

701.3. Many other factors should be considered in demonstrating compliance. These include, but are not limited to, the complexity of the package design, special phenomena that require investigation, the availability of facilities, and the ability to accurately measure and/or scale responses.

701.5 ... If simulated radioactive contents are being used, these contents should truly represent the actual contents in mass, density, chemical composition, volume and any other characteristics that are significant. The contents should simulate any impact loads on the inside surface of the package and on any closure lids. ...

Especially para 701.5 [10] points out the need for an adequate consideration of the internal interactions in the mechanical safety assessment. This does not necessarily mean that the maximum gap size has to be immediately modeled in the drop test. Any adjustment of the package and its content relative to one another in the “pre-drop” configuration to set the maximum design gaps is in the most cases not practicable, especially in the drop tests with full scale models of heavy packages. The relevant effects can also be analyzed numerically by verified or conservative approaches.

BAM supports an improvement of guidance for the transport regulations on this issue. The amendment should give applicants for package approval better guidance, reduce rounds of questions and ensure the delivery of reliable safety case documents to the competent authorities. The following enhanced guidance of para 701.5 was proposed by France and Germany and discussed during several IAEA member states meetings:

701.5 ... If simulated radioactive contents are being used, these contents should truly represent the actual contents in mass, mechanical stiffness, density, chemical composition, volume and any other characteristics that are significant. The contents should simulate any impact loads on the inside surface of the package and on any closure lids including internal collision effects in case of not fixed contents. Since the intensity of internal collisions under likely incidents or accidents substantially depends on the initial gaps between contents and envelope structure, the most damaging position of contents within package cavity should be either simulated directly in drop test or, if it is not practicable, suitably incorporated in structural analysis ...

Summary and conclusions

The interaction between package lid system and internal content during mechanical drop testing is of decisive matter to evaluate impact loads and the safety of the package. In case of a movable content its impact onto the inner side of the package lid can cause additional load peaks on the lid

and the lid bolts. Due to physical limitations an axial gap, which could be set in “pre-drop” configuration of package or which could spontaneously appear during the drop test, usually does not cover the maximum size possible in specific package design. In this context, the combination of drop tests with post-test analysis can be helpful to better estimate the effect of internal impact.

Quasi-static calculation models are often used for the mechanical assessment of the package lid system. The content is modeled by inertial force derived from the maximum rigid body deceleration. The question whether the real content/lid interaction is covered by this assumption is infrequently addressed in the package design safety reports. Such analysis is challenging due to the large number of parameters of the mechanical system involved, so that an unambiguous general solution is difficult and in many cases impossible to obtain. The qualitative analysis presented in this paper demonstrates the limitations of the quasi-static models for the mechanical assessment of the lid system: the approach based on the maximum rigid-body deceleration of the package is applicable only for certain combinations of its parameters.

The domain of applicability expands with increasing stiffness of the impact limiter and decreasing stiffness of the content. This common nearly obvious conclusion can be useful in the design process. Moreover, the dynamic load factors for possible dynamic amplifications in the vibration response of the lid system have to be included in the load assumptions of the quasi-static model.

In order to gain a better understanding of the effects observed in the 9 m vertical drop test with a full scale package performed by BAM, an analytical MDOF model was used. The calculation results correlates well with the experimental measured decelerations and strains before and during the internal impact phase. With this model the influence of the gap size onto the loading of the lid is considered.

The examples presented in the paper demonstrate the governing character of the axial gap size for the lid loading due to an internal content/lid collision. The principal question is: Which gap size should be taken into account in the mechanical assessment of the lid system?

The current International Transport Regulations with the corresponding Advisory Material does not include any explicit requirements concerning this subject. Two different interpretations of the regulatory statements are applied.

BAM supports improvement of guidance for the transport regulations on this issue. The amendment should give applicants for package approval better guidance, reduce rounds of questions and ensure the delivery of reliable safety case documents to the competent authorities.

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