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SUGGESTIONS FOR CORRECT PERFORMANCE OF IAEA 1 M PUNCTURE BAR DROP TEST WITH REDUCED-SCALE PACKAGES CONSIDERING SIMILARITY THEORY ASPECTS

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ABSTRACT
In this paper the IAEA regulatory 1m puncture bar drop test is considered from the viewpoint of using reduced-scale model packages. The similarity theory will be represented with regard to the practical performing of the puncture test. To reach an energy input into the containment boundary of a reduced-scale model, that is equivalent to a full-scale package, the drop height has to be higher than 1 m. A general approach for the calculation of the drop height correction was derived depending on the scale factor. Complementary numerical calculations showed that the influence of a drop height adaptation becomes more important with larger scale factors.
Furthermore it is shown that, a drop height adaptation must be considered not only for drop tests with a deep penetration of the puncture bar (due to a thick deformable outside structure), but also for puncture bar drop tests with direct impact onto the containment boundary especially if scale models with larger scale factors are used.

INTRODUCTION
In the approval procedure of transport packages for radioactive materials, the competent authority mechanical and thermal safety assessment is carried out in Germany by BAM on the basis of the IAEA regulations [1]. Computational methods and experimental investigations are both used for the safety assessment. The combination of the methods in addition with materials and cask components testing is the basis of an assessment concept of BAM, considering the state of the art.
The experimental tests according to IAEA regulations [1] are frequently carried out with reduced-scale models. However, it must be considered that a reduced-scale model can show a different behavior during testing in comparison to a full-scale prototype cask. The correct use of similarity laws in connection with the test aims have to be used appropriately in the safety assessment procedure. Doing this, the IAEA regulations [1] and the advisory material [2] must be interpreted and applied correctly.
In particular for drop tests, where the impact load of the test object is dependent on the released potential energy, and the characteristic deformation of the structure is noteworthy in comparison to the drop height, special considerations are necessary.
In this paper the IAEA 1 m puncture bar drop test ([1], §727 (b)) is critically investigated from the viewpoint of its correct application when using reduced-scale model packages. The similarity theory will be represented with regard to the practical performance of the puncture test. To reach

an energy input into the containment boundary of a reduced-scale model that is equivalent to a full-scale model, the drop height has to be higher than 1 m. A general approach for the calculation of the drop height correction will be derived depending on the scale factor. An example calculation illustrates the procedure. Complementary numerical calculations will show that the influence of a drop height adaptation becomes more important with larger scale factors.
Furthermore it is shown that, a drop height adaptation must be considered not only for drop tests with a deep penetration of the puncture bar (due to a thick deformable outside structure), but also for puncture bar drop tests with direct impact onto the containment boundary, especially if scale models with larger scale factors are used.

DESCRIPTION OF THE PROBLEM

A geometrically similar model of a package (index: M) with a scale of 1:λ is supposed to be used for the IAEA drop tests [1]. The length values are scaled to equation (1).

$$L_{\mathrm{O}} = \lambda \cdot L_{\mathrm{M}} \tag{1}$$

For the model to apply, it must be guaranteed that the load of the reduced-scale model caused by the drop test is representative for the load that would occur in a test object of original size (index: O). With regard to the complete similarity of two mechanical phenomena it is not sufficient if only the geometrical similarity is considered. For example an exact similarity [3], [4] is not possible, if the investigations of an accelerated movement caused by different loading classes (gravity, elastic loads etc.) are carried out at a reduced-scale model consisting of the same materials as the original cask [5], [7]. Additional considerations are necessary if the loading of the test object for certain drop tests depends on the released potential energy. It is especially important that tests with an appreciable characteristic deformation of the package structure, compared to the drop height, be considered. In this case the loss of the potential energy over the deformation path is noteworthy in comparison to the impact energy.
The comments and explanations in this paper refer to experiments with geometrically similar models. The test object consists of the same materials as the original size package. Considering the scaling of the model cask, the energy balance is derived for the corresponding puncture drop test (see equation (2)).
The inserted energy has to follow the laws of similarity during the drop test (equations (2) and (3)). The energy refers to the entire test object and/or the structural element which is the item being assessed:

total energy: $$E_{\mathrm{O}} = \lambda^3 \cdot E_{\mathrm{M}} \tag{2}$$

change of energy: $$\Delta E_{\mathrm{O}} = \lambda^3 \cdot \Delta E_{\mathrm{M}} \tag{3}$$

In this context it is important to have a closer look to the IAEA 1 m puncture test [1] where a containment boundary is the item being assessed (e.g. lid system or cask wall) that is surrounded by a significant thick deformable structure (e.g. impact limiting or neutron shielding material).
In this case the use of a reduced-scale model package, while maintaining a drop height of 1 m measured from the intended point of impact at the outer surface of the package to upper surface of the penetration bar leads to a lower specific energy input than in case of a full-scale package.
Such a drop test with a reduced-scale package would not meet the IAEA test conditions!
Drop tests with a deep penetration of the bar into the surrounding surface of the package before impacting the containment boundary are currently an exemplary case. In comparison to other drop test situations a significantly higher drop height must be considered if a reduced-scale model cask is used. Precise considerations to the similarity theory result also in puncture tests with an impact directly onto the con-tainment boundary (e.g. cask body) and, in the event of a

significant deformation of the penetration bar, to an adaptation (increase) of the drop height because of the use of a reduced-scale model.

The paragraphs of the IAEA regulations [1], necessary for the realization of the drop test: §701 (c) and §727 (b) give only general recommendations:

[1], §701 (c): "Performance of tests with models of appropriate scale incorporating those features which are significant with respect to the item under investigation when engineering experience has shown results of such tests to be suitable for design purposes. When a scale model is used, the need for adjusting certain test parameters, such as penetrator diameter or compressive load, shall be taken into account."

[1], §727 (b): "For drop II, the specimen shall drop so as to suffer maximum damage onto a bar rigidly mounted perpendicularly on the target. The height of the drop measured from the intended point of impact of the specimen to the upper surface of the bar shall be 1 m. The bar shall be of solid mild steel of circular section, (15.0 ± 0.5) cm in diameter and 20 cm long unless a longer bar would cause greater damage, in which case a bar of sufficient length to cause maximum damage shall be used. The upper end of the bar shall be flat and horizontal with its edge rounded off to a radius of not more than 6 mm. The target on which the bar is mounted shall be as described in para. 717."

The adaptation of the drop height is referred to the IAEA Advisory Material, §701.19 [2], but very clear details of realization are not specified. In this case the explanation refers to the penetration of the bar exclusively if the package has an appreciable thick deformable structure (e.g. impact limiter):

[2], §701.19: "… In some tests, such as the penetration tests specified in the Regulations, the bar should be scaled in order to produce accurate results. In other cases where the packaging may be protected by a significant thickness of deformable structure, the drop height ***may need to be scaled***."

In the following the procedure for the determination (i.e. the correction or scaling) of the drop height is shown for the puncture test of a reduced-scale model package.

APPLICATION OF THE SIMILARITY THEORY

Considerations on the Energy Balance

The correction of the drop height of the model cask is based on the principle of conservation of energy according to the consideration of the initial state (i.e. before the drop test) and the final situation after the test. Fig. 1 shows an example of a vertical puncture bar drop test with deep penetration of the bar into a deformable structure, before hitting the containment boundary.

Energy balance, generally - The released potential energy during the drop is

$$\begin{aligned}\Delta E_{\mathrm{pot}} &= E_{\mathrm{pot,\,IS}} - E_{\mathrm{pot,\,FS}} \\ &= m \cdot g \cdot \left(l_{\mathrm{CG}} + x + l_{\mathrm{B}}\right) - m \cdot g \cdot \left(l_{\mathrm{CG}} - u_{\mathrm{C}} - u_{\mathrm{IL}} + \left(l_{\mathrm{B}} - u_{\mathrm{B}}\right)\right) \\ &= m \cdot g \cdot \left(x + u_{\mathrm{C}} + u_{\mathrm{IL}} + u_{\mathrm{B}}\right)\end{aligned} \tag{4}$$

with u_{C}, u_{IL} und u_{B} as characteristic plastic deformations of the cask, the impact limiter and the penetration bar after the drop test. Considering that, at the end of the impact, this energy is completely transformed into the deformation energies of the cask $E_{\mathrm{C}}(u_{\mathrm{c}})$, the impact limiter $E_{\mathrm{IL}}(u_{\mathrm{IL}})$ and the penetration bar $E_{\mathrm{B}}(u_{\mathrm{B}})$ (inertia effects are assumed to be minimal) the energy balance is

$$\Delta E_{\mathrm{pot}} = E_{\mathrm{C}}\left(u_{\mathrm{C}}\right) + E_{\mathrm{IL}}\left(u_{\mathrm{IL}}\right) + E_{\mathrm{B}}\left(u_{\mathrm{B}}\right) \tag{5}$$

whereas, the distribution of the energies between the impact partners depends mainly on their resiliencies. For a full-scale package (drop from a height x_{O}) is:

$$E_{\mathrm{C,O}}\left(u_{\mathrm{C,\,O}}\right)=m_{\mathrm{O}}\cdot g\cdot\left(x_{\mathrm{O}}+u_{\mathrm{C,\,O}}+u_{\mathrm{IL,\,O}}+u_{\mathrm{B,\,O}}\right)-E_{\mathrm{IL,O}}\left(u_{\mathrm{IL,\,O}}\right)-E_{\mathrm{B,O}}\left(u_{\mathrm{B,\,O}}\right) \tag{6}$$

For a reduced-scale model package (drop height x_{M}) with a mass scaling of $m_{\mathrm{M}}=m_{\mathrm{O}}/\lambda^3$ is:

$$E_{\mathrm{C,M}}\left(u_{\mathrm{C,M}}\right)=m_{\mathrm{M}}\cdot g\cdot\left(x_{\mathrm{M}}+u_{\mathrm{C,\,M}}+u_{\mathrm{IL,\,M}}+u_{\mathrm{B,\,M}}\right)-E_{\mathrm{IL,M}}\left(u_{\mathrm{IL,\,M}}\right)-E_{\mathrm{B,M}}\left(u_{\mathrm{B,\,M}}\right) \tag{7}$$

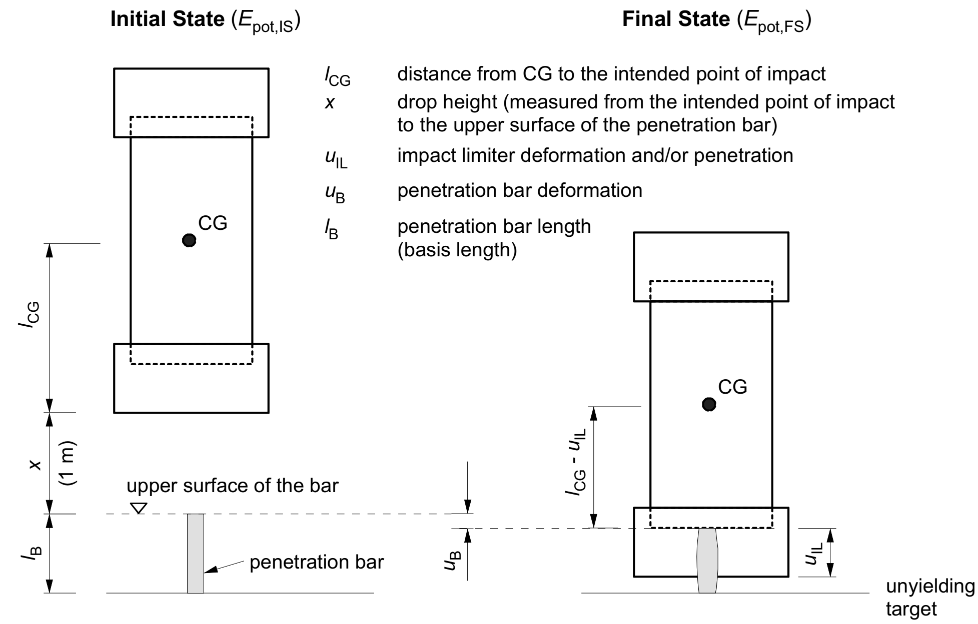

Figure 1. Drop test positions (vertical puncture bar drop test)

The drop height x_{M} for the reduced-scale model package can be derived on the basis of similarity of its deformation energy to one of a full-scale package at the drop height x_{O}. The energy relation for a geometrical and material similar model is like equation (2) for all impact partners, i.e.:

$$E_{\mathrm{i,O}}\left(u_{\mathrm{i,O}}\right)=\lambda^3\cdot E_{\mathrm{i,M}}\left(u_{\mathrm{i,M}}\right)=\lambda^3\cdot E_{\mathrm{i,M}}\left(\frac{u_{\mathrm{i,O}}}{\lambda}\right)\qquad \text{for } i=C,\,IL,\,B \tag{8}$$

In this case the ratio between the resiliencies of the impact partners is maintained. Thus it is assumed that the relative energy distribution is equal too. The following relationship is derived from equation (2) to (8):

$$\begin{aligned}E_{\mathrm{C,O}}\left(u_{\mathrm{C,O}}\right)\quad &=m_{\mathrm{O}}\cdot g\cdot\left(x_{\mathrm{O}}+u_{\mathrm{C,O}}+u_{\mathrm{IL,O}}+u_{\mathrm{B,O}}\right)-E_{\mathrm{IL,O}}\left(u_{\mathrm{IL,O}}\right)-E_{\mathrm{B,O}}\left(u_{\mathrm{B,O}}\right)\\ &=\lambda^3\cdot E_{\mathrm{C,M}}\left(\frac{u_{\mathrm{C,O}}}{\lambda}\right)\\ &=\lambda^3\left[\frac{1}{\lambda^3}\cdot m_{\mathrm{O}}\cdot g\cdot\left(x_{\mathrm{M}}+\frac{u_{\mathrm{C,O}}}{\lambda}+\frac{u_{\mathrm{IL,O}}}{\lambda}+\frac{u_{\mathrm{B,O}}}{\lambda}\right)-E_{\mathrm{IL,M}}\left(\frac{u_{\mathrm{IL,O}}}{\lambda}\right)-E_{\mathrm{B,M}}\left(\frac{u_{\mathrm{B,O}}}{\lambda}\right)\right]\end{aligned} \tag{9}$$

<u>Drop Height Adaptation in General</u>

In consideration of x_{O}=1 m (original IAEA puncture test drop height [1] for a full-scale package), equation (9) is re-arranged to x_{M} as shown in in equation (10), which represents the calculation of the drop height correction if a reduced-scale model package is used.

$$
\begin{aligned}
x_{\mathrm{M}} &= 1\ \mathrm{m} + \left(u_{\mathrm{C,O}} + u_{\mathrm{IL,O}} + u_{\mathrm{B,O}}\right) - \left(\frac{u_{\mathrm{C,O}}}{\lambda} + \frac{u_{\mathrm{IL,O}}}{\lambda} + \frac{u_{\mathrm{B,O}}}{\lambda}\right) \\
&= 1\ \mathrm{m} + \frac{\lambda - 1}{\lambda} \cdot \left(u_{\mathrm{C,O}} + u_{\mathrm{IL,O}} + u_{\mathrm{B,O}}\right)
\end{aligned}
\tag{10}
$$

The given equation is consistent with the IAEA regulations [1]. The required IAEA drop height of 1 m is calculated for a full-scale package (λ=1).

The geometrical values diameter of the penetrator bar (D_{B}) and penetration depth (u_{IL}) follow the similarity laws according to equation (11) and (12).

$$D_{\mathrm{B,O}} = \lambda \cdot D_{\mathrm{B,M}} \tag{11}$$

$$u_{\mathrm{IL,O}} = \lambda \cdot u_{\mathrm{IL,M}} \tag{12}$$

Thus, to define the correct drop height for reduced-scale models (see equation (10)) it is necessary to pre-calculate or estimate original size deformations of the cask ($u_{\mathrm{C,O}}$), the impact limiter ($u_{\mathrm{IL,O}}$) and the penetrator bar ($u_{\mathrm{B,O}}$). Generally the deformation of the cask body will be insignificant with regard to the drop height correction. On the other hand it is important to consider the deformation u_{IL} for a deep penetration of the bar into shock-absorbing structures, e.g. wood filled impact limiters.

Drop Height Adaptation considering Puncture Bar Compression

A more precise consideration of the deformation of the penetration bar may be necessary. The smaller deformation path (absolute value) of the penetration bar during the drop test with a geometrically scaled model cask leads to a discrepancy in the similarity of the energy between full-scale and reduced-scale model test. An adaptation of the drop height can balance this effect. The experience of BAM with reduced-scale model casks shows that for the planning of drop tests, including the determination of appropriate drop heights, analytical estimates or better numerical pre-calculations with realistic material values are reasonable.

The effect of the dimension of a drop height adaptation depends particularly on the scale factor λ. The larger this factor (i.e. the smaller the model), the larger is the adjustment of the drop height (see equation (10)).

Fig. 2 shows results of example calculations on the basis of appropriate geometry and material parameters. The analytical estimate for the case of the drop of a rigid body onto a penetrator bar considers only the bar deformation. The calculated adaptation of the drop height after equation (10) refers to the correct scaling of the deformation energy of the penetrator bar and consequently its effect on the dropping body for different scaling factors. In consideration of a static strength curve of the bar material it can be estimated already for a 1:8 scale model an adaptation of the drop height around 11% up to 1.11 m. This case is also relevant for puncture tests with direct impact of the bar onto the cask body without covering impact limiters.

Using more precise numeric calculations (finite element analysis) that consider strain rate dependent strength curves and material hardening, a further correction of the drop height, in the example around 16 % up to 1.16 m, is necessary. The analyses were carried out only with strain rate dependent strength curves for the penetrator bar. According to similarity theory, reduced-scale models show higher strain rates with a higher material hardening (cp. equation (13)).

$$\dot{\varepsilon}_O = \frac{\dot{\varepsilon}_M}{\lambda} \tag{13}$$

Obviously the assumed similar relative yield of the impact partners for the reduced-scale model test and the full-scale test based on the derivation of equation (9) are not given in the strict sense. The stiffer behavior of the reduced-scale model package needs a further increase of the drop height (equation (10)). The illustration in Fig. 2 shows the dependence of the drop height correction resulting from the scale factor and the effect of the dynamic material hardening. It is noteworthy that the example calculations support the IAEA Advisory Material [2], §701.20 statement, that the difference in the strain rate dependent material behavior between model and prototype casks and the effects resulting from that up to a scale factor of λ=4 are negligible.

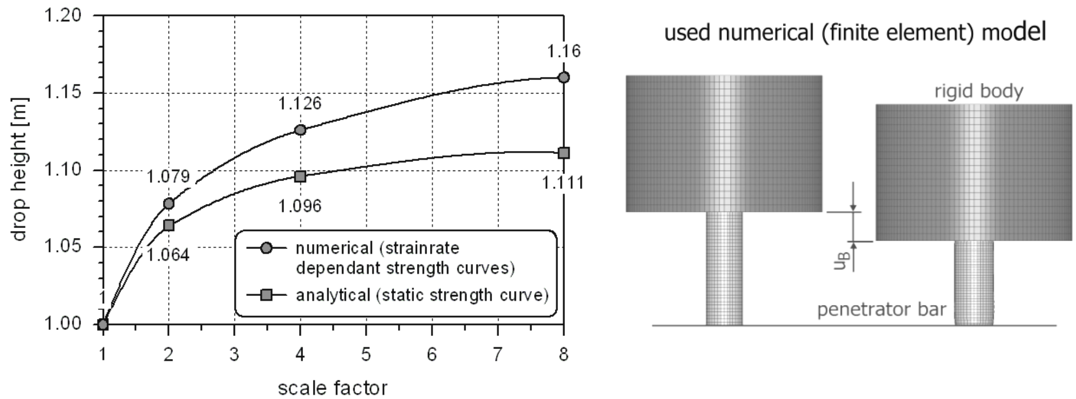

Figure 2. The dependency of the drop height from the scaling factor for the case of a drop height adaptation considering penetrator bar compression

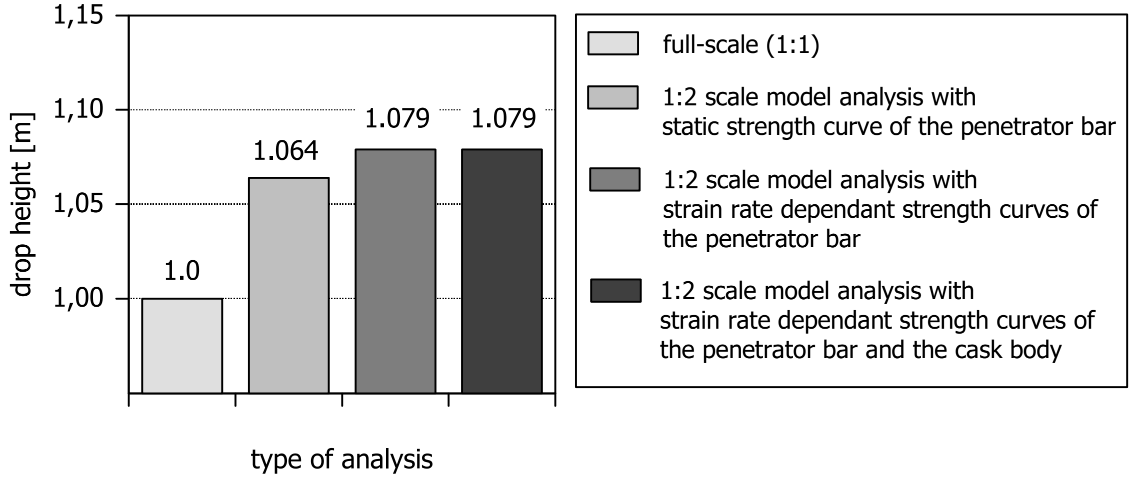

Figure 3. The dependency of the drop height adaptation for a chosen 1:2 scale model from the kind of analysis

Simple methods can be shown to be useful in estimating the needed modification in drop heights for scale model packages. Additionally, Fig. 3 represents, that precise numeric pre-calculations carried out by extensive finite element analyses considering strain rate dependent strength curves for just the cask body and the penetrator bar and a detailed modeling of the geometry show only an insignificant increase in the drop height adaptation.

PRACTICAL APPLICATION

Example of a Complete Calculation of the Drop Height Adaptation

Assume that it is planned to check the operability (leak tightness) of the lid system of the package represented in Fig. 4 under an IAEA puncture bar drop test with a 1:2 scale model (equation (1)).

For this case the drop height correction can be estimated as follows:

- A relatively stiff behavior of the lid system is assumed. So, the deformation of the lid can be neglected. It is $u_{C,O} \approx 0$ in equation (10).

- It is supposed that the soft wooden layers inside the impact limiter are punched through to the lid. In this case the deformation $u_{\mathrm{IL,O}}$ in equation (10) is equal to the original thickness of the wooden layers, therefore $u_{\mathrm{IL,O}} = 0.60$ m.

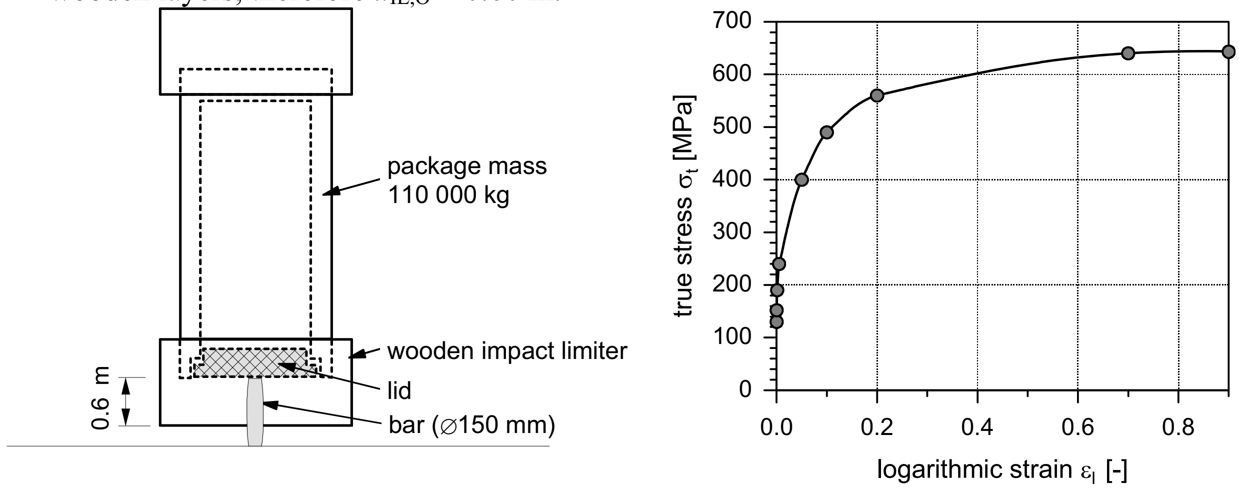

Figure 4. Example of a puncture bar drop test (full-scale package) and "synthetic" strength curve of the chosen penetrator bar material (mild steel)

- The determination of the drop height correction resulting from the penetrator bar deformation is assumed by the following load-deformation-function:

$$F_{\mathrm{B}}\left(u_{\mathrm{B}}\right)=\frac{\pi \cdot D_{\mathrm{B,O}}{}^{2}}{4 \cdot\left(1-\frac{u_{\mathrm{B}}}{l_{\mathrm{B}}}\right)} \cdot \sigma_{\mathrm{t}}\left(\varepsilon_{\mathrm{l}}\left(u_{\mathrm{B}}\right)\right) \tag{14}$$

In this equation u_{B} represents the penetrator bar deformation and is the functional description of the static strength curve of the penetrator bar material (see Fig. 4) as true stress-logarithmic plastic strain relationship. The synthetic true stress-strain curve (Fig. 5) considers a mild steel according to [2] §727.13. Furthermore equation (14) considers the cross section area increase of the bar while under compression using the assumption of a constant volume. The conservative estimate of the maximum bar deformation results from the additional assumption that the energy absorbed while punching through the impact limiter and by the deformation of the lid is small in comparison with the impact energy. From the law of the conservation of energy, the results are then:

$$m \cdot g \cdot\left(1.0 \text{ m}+0.6 \text{ m}+u_{\mathrm{B,O}}\right)=\int_{0}^{u_{\mathrm{B,O}}} F_{\mathrm{B,O}}\left(u_{\mathrm{B}}\right) \mathrm{d} u_{\mathrm{B}} \tag{15}$$

The maximum penetrator bar deformation $u_{\mathrm{B,O}}$=0.17 m follows from equation (15) with a mass of the package of m=110 000 kg. For the chosen example the final drop height for the 1:2 scale model package test x_{M}=1.385 m (see equation (16)) is calculated using equation (10).

$$x_{\mathrm{M}}=1 \text{ m}+\frac{2-1}{2} \cdot(0.60 \text{ m}+0.17 \text{ m})=1.385 \text{ m} \tag{16}$$

<u>Practical Test Examples</u>

Fig. 5 shows different examples of drop height adaptations of IAEA puncture tests with deep penetration of the bar from the experimental practice of BAM [6]. The figure represents the drop heights of a prototype cask (1:1, Castor® Ic) and two reduced-scale model casks (1:2, Castor® HAW/TB2 und 1:3, TN81). The chosen examples clearly demonstrate the great range of the adaptations (here: up to 30%).

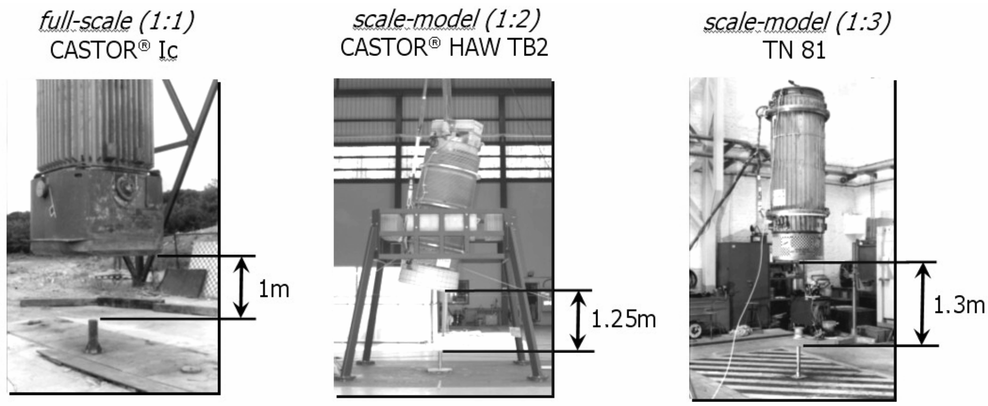

Figure 6: Puncture bar drop test examples with full-scale and reduced-scale model packages

CONCLUSIONS

If reduced-scale model packages are used for the mechanical IAEA tests, special attention should be concentrated on the correct use of the similarity mechanics theory. In particular, special considerations are necessary for drop tests where the impact load of the test object is dependent on the released potential energy, and where the characteristic deformation of the structure is not negligible in comparison to the drop height.

For the puncture bar drop test the similarity mechanical considerations are described. A general approach for the calculation of the drop height correction was derived for different puncture tests depending on the scale factor. An example calculation illustrated the procedure. Complementary numeric calculations showed that the influence of adapted drop height becomes more important with greater scale factors.

Furthermore with respect to recommendations of the IAEA Advisory Material ([2] §701.19), it was elaborated that adapted drop height must be considered not only for drop tests with a deep penetration of the bar (due to an appreciably thick deformable structure), but also where appreciable penetrator bar compression resulting from direct impact onto the containment boundary is expected. The adapted drop heights become more significant when reduced-scale models with large scale factors are used.

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