Suggestions for the Correct Performance of IAEA 1 m Puncture Bar Drop Test with Reduced Scale Packages Considering Similarity Theory Aspects

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Introduction

- possibility of using *reduced scale models* for IAEA regulatory drop tests
- different behavior between full scale and reduced scale test models
- correct application of *similarity theory* of particular importance
- special considerations at drop tests, where:
  - noteworthy *deformation* of the structure in comparison to drop height
- *consequence*: possible adaptation of the boundary conditions (e.g. drop height) of the IAEA drop test specifications
- BAM experience: special attention should be paid to *IAEA 1m puncture bar drop test*

**GOAL:**

introduction of a general approach for the calculation of the *drop height correction*
General recommendations in the IAEA Regulations (TS-R-1).

§701 (c):
“Performance of tests with models of appropriate scale incorporating those features which are significant ... 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.”

§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, ...”
IAEA Advisory Material refers to an adaptation of the drop height
very clear details of realization are not specified
the explanation refers to the penetration of the bar exclusively if the package has an appreciable thick deformable structure (e.g. impact limiter)

§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.”
Similarity

Basis of the reduced-scale model: geometrical scaling, same material

\[ L_O = \lambda \cdot L_M \]
\[ \lambda \ldots \text{scale factor} \]

The inserted energy has to follow the laws of similarity during the drop test:

\[ E_O = \lambda^3 \cdot E_M \]
\[ \Delta E_O = \lambda^3 \cdot \Delta E_M \]

- **special attention**: IAEA puncture bar drop test 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.

- reduced-scale model: *lower specific energy input* than in case of a full-scale package, while maintaining a drop height of 1 m

- Such a drop test with a reduced-scale package would *not exactly meet* the IAEA test conditions!
Similarity (Energy Balance)

drop height correction bases on the *principle of conservation of energy*

**released potential energy:**

\[ \Delta E_{\text{pot}} = E_{\text{pot}, \text{IS}} - E_{\text{pot}, \text{FS}} \]

After impact, complete transformation into deformation energies:

\[ \Delta E_{\text{pot}} = E_C(u_C) + E_{\text{IL}}(u_{\text{IL}}) + E_B(u_B) \]

\[ \Delta E_{\text{pot},0} = m_0 \cdot g \cdot \left( x_0 + u_{C,0} + u_{\text{IL},0} + u_{B,0} \right) = E_{C,0}(u_{C,0}) + E_{\text{IL},0}(u_{\text{IL},0}) + E_{B,0}(u_{B,0}) \]

\[ E_{\text{pot}, \text{IS}} - E_{\text{pot}, \text{FS}} \]
Example: vertical puncture drop test with *deep penetration* of the bar into a deformable structure (impact limiter)

**Initial State** \( (E_{\text{pot,IS}}) \)  
**Final State** \( (E_{\text{pot,FS}}) \)

- Initial State: \( l_B \) (penetration bar), \( x \) (distance), CG (center of gravity)  
- Final State: \( l_{CG} \) (penetration), \( u_B \) (displacement), CG (center of gravity), unyielding target
The drop height for the reduced-scale model can be derived on the basis of similarity of its deformation energy to one of a full-scale package at the drop height 1m.

\[
E_{i,O} \left( u_{i,O} \right) = \lambda^3 \cdot E_{i,M} \left( u_{i,M} \right) = \lambda^3 \cdot E_{i,M} \left( \frac{u_{i,O}}{\lambda} \right) \quad \text{for } i = C, IL, B
\]

**Drop height correction**  
(drop height for the reduced-scale model test):

\[
x_M = 1 \text{ m} + \frac{\lambda - 1}{\lambda} \cdot \left( u_{C,O} + u_{IL,O} + u_{B,O} \right)
\]

- scale factor
- cask
- impact limiter
- bar (deformations)
Practical Application (example)

- 1:2 drop test model
- lid deformation neglected \((u_{c,o} \approx 0)\)
- impact limiter completely punched by bar
- *static strength* curve of the bar material used for calculation of bar deformation

Load-deformation function:

\[
F_B(u_B) = \frac{\pi \cdot D_{B,O}}{4 \cdot \left(1 - \frac{u_B}{l_B}\right)} \cdot \sigma_t \left(e_i(u_B)\right)
\]

\[
m \cdot g \cdot (1.0 \text{ m} + 0.6 \text{ m} + u_{B,O}) = \int_0^{u_{B,O}} F_{B,O}(u_B) \, du_B \quad \Rightarrow \quad u_{B,O} = 0.17 \text{ m}
\]

\[
x_M = 1 \text{ m} + \frac{2 - 1}{2} \cdot (0.60 \text{ m} + 0.17 \text{ m}) \approx 1.39 \text{ m} \quad \Rightarrow \quad 39\% \text{ increasing}
\]
Practical Test Examples

- examples taken from BAM test experience
- drop testing with full-scale and reduced-scale models during different type testing procedures over the last decades

full-scale (1:1) CASTOR® Ic

scale-model (1:2) CASTOR® HAW TB2

scale-model (1:3) TN 81
Summary and Conclusions

- correct use of the *similarity theory*, if reduced-scale model packages are used for the IAEA drop tests

- particular importance for drop tests where the characteristic *deformation of the structure* is not negligible in comparison to the drop height

- general approach for drop height correction, depending on the scale factor
  - simple method/equation for estimate drop height correction purposeful

- The correction of the drop height becomes more significant when reduced-scale models with *large scale factors* are used.

- with respect to IAEA Advisory Material (§701.19):
  adaptation of drop height not only for drop tests with a *deep penetration* of the puncture bar (due to an appreciably thick deformable structure), but also where appreciable *puncture bar compression* resulting from direct impact onto the containment boundary is expected