Proceedings of the 15th International Symposium on the Packaging and Transportation of Radioactive Materials
PATRAM 2007
October 21-26, 2007, Miami, Florida, USA

COMPARISON OF EXPERIMENTAL RESULTS FROM DROP TESTING OF A SPENT FUEL PACKAGE DESIGN USING A FULL-SCALE PROTOTYPE MODEL AND A REDUCED-SCALE MODEL

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ABSTRACT
This paper presents a comparison between full-scale prototype and reduced-scale model drop test data in regard to similarity mechanics. Together with a current BAM research project, the paper contributes to the further development of mechanical evaluation methods for safety assessment of RAM transport and storage packages including the transferability of package impact response from reduced-scale models to full-scale packages.

INTRODUCTION
In the context of approval design tests according to IAEA-Regulations and the evaluation of packaging response to mechanical tests demonstrating safety under accident conditions, drop testing reduced-scale models is an established and accredited method considering existing constraints, limitations and safety margins.
As part of a current BAM research project and design approval testing, a full-scale prototype of a package for transport and storage of spent fuel elements and its reduced-scale model were drop tested in 9 m and 1 m puncture tests at various drop orientations under regulatory conditions. By analyzing experimental data comparing the package impact responses of the prototype and model, the paper shows analysis results of the similarity performance capability of the scale-model. Comparison of the analyzed experimental data shows that the similarity of the impact response between the scaled and prototype model depends on many influencing phenomena and determining parameters besides the immanent limitations of the scaling model applied. By determining some of the influencing phenomena, the paper also examines the difficulties and limitations using scale model testing. The research is initially specific and related to the package design investigated in connection with the controlling drop test conditions. However, it shows that omitted effects must be identified and possible errors taken into account when using the results.

SPECIMEN AND DROP TEST SCALE MODEL
The specimens are a full-scale prototype of a package for transport and storage of spent fuel elements and its scaled 1:2.5 model. The package is made of a forged steel cask body closed by a double lid system with metallic seals. Impact protection is provided by shock absorbers (wood composite /steel construction) on the bottom and lid of the cask. The cask is assembled with

basket tubes and dummy-fuel elements. For neutron shielding the cask body is bonded by a resin coating protected on the outside with a steel layer. The package has a total mass of 127,000 kg (scaled model: 8,010 kg), the contents a total mass of 21,000 kg (scaled model: 1430 kg) and the total length including shock absorbers is 6810 mm (model: 2724 mm). For more technical details of the package see [R1].

In respect to most components, the scaled model cask is almost completely similar to the prototype in both geometry and design. Exceptions are metal gasket diameter and the corresponding geometry of the grooves. As far as possible all components are made of identical material and the material properties of the prototype and model are close together.

The applied drop test scale model comprises the complete impact response including wave and vibration but omitting strain-rate and gravity effects. It has only one independent scaling factor namely the geometry scaling factor s_l , which is defined as the ratio of a length in the scaled model to that in the prototype cask. It determines the scaling factors for all other parameters. The scale factor chosen is 1:2.5 (s_l = 0.4). Drop conditions as drop height, impact velocity, drop angle, cask orientation and unyielding target are identical for both the scaled model and the prototype. As a result of the accordant scaling law, scaling factors for the basic dimensions e.g. time and mass are s_l (value 0.4) and s_l^3 (value 0.064), for the rigid body motion as e.g. translation and deceleration are s_l (value 0.4) and s_l^{-1} (value 2.5) and for structural response, e.g. stress and strain are the same for both model and prototype (value 1.0): see [R2].

TEST CONDITIONS AND METROLOGY

Altogether three comparable drop tests were performed at the BAM's 200 ton drop test facility with the prototype and scaled cask model to investigate drop test performance under similarity conditions. *Figure 1* shows exemplarily by means of the prototype the three types of drop tests.

Figure 1. Drop Tests. Vertical, Oblique and Horizontal Cask Orientation.

In the 9.3 m vertical drop test (*Figure 1, left.*) the lid system is facing downwards. In the 9 m oblique drop test the specimen has an impact angle of 10° causing a secondary impact -the slap-down impact- to the lid side (*Figure 1*, *middle*). The puncture bar in the horizontal drop test targets the edge of the secondary lid (*Figure 1, right*). Drop height is 1 m for the prototype and 1.25 m for the scaled cask model, so as to get a comparable impact energy acting on the containment boundary: see [R3].

The drop tests were conducted with continuous monitoring of strains and accelerations at appropriate locations on the cask body, lids and lid bolts to get the transient impact responses of the specimens. The coordinates of all measurement points on the prototype were transferred by the scaling factor s_l to the model, and the grid length of strain gauges was scaled according to the available product specification. Choice of transducers and data acquisition devices considered the shorter impact duration, higher decelerations and natural vibration frequencies of the scaled model.

COMPARISON OF TEST RESULTS IN REGARD TO SCALING LAW

The comparison of test results in regard to scaling law focuses on the rigid body impact and structural impact response of the cask body, primary/secondary lid and lid bolts. It is mainly based on the analysis of measured strain and acceleration time signals.

In a first approach, the comparison considered variation in time and characteristic single values of strain/deceleration histories. By analyzing the qualitative variation in time significant impact phenomena were identified and compared between prototype and model. Characteristic single values for both the rigid body and structural impact response, e.g. maximum deceleration, impact duration, maximum stress and strain, etc., were determined. Furthermore the ratio r of a characteristic single value in the model to the corresponding value in the prototype was compared to the theoretical scale factor s to calculate the relative deviation $\boldsymbol{\Delta}$ with $\Delta = 100\ \% \cdot s^{-1} \cdot (r - s)$. A positive deviation means that the characteristic is overvalued, and a negative that it is undervalued, by the scale model.

The following strain- and deceleration-time diagrams show original measurement curves of the prototype and model during impact. The deceleration curves are low-pass filtered with a cut-off frequency so that they represent approximately the rigid body motion of the cask. In the diagrams the time range and ordinate axis of the deceleration and strain curves for the scale-model is adapted to the theoretical scale factor s. Thus, a visual comparison between prototype and model in regard to similarity is easier - the more congruence, the better the similarity.

Comparison of the analyzed experimental data shows that similarity in the impact response of the scaled and prototype model depends on many influencing phenomena and determining parameters besides the immanent limitations of the scaling model applied. Influencing phenomena like size and strain-rate effects of the wood composite as well as friction effects between the wood contents and steel sheet coating play a decisive role in the force-deformation behavior of the shock absorber, which mainly guides the impact response of the cask: see [R4]. Further limitations come from the omission of gravity effects on the impact behavior of the contents. In using the results, omission of these effects must be taken into account, as the following examples show.

9 m Vertical Drop Test

Impact responses concerning the rigid body motion of specimens are described basically by their low- pass filtered deceleration and velocity time histories. *Figure 2* illustrates comparatively the

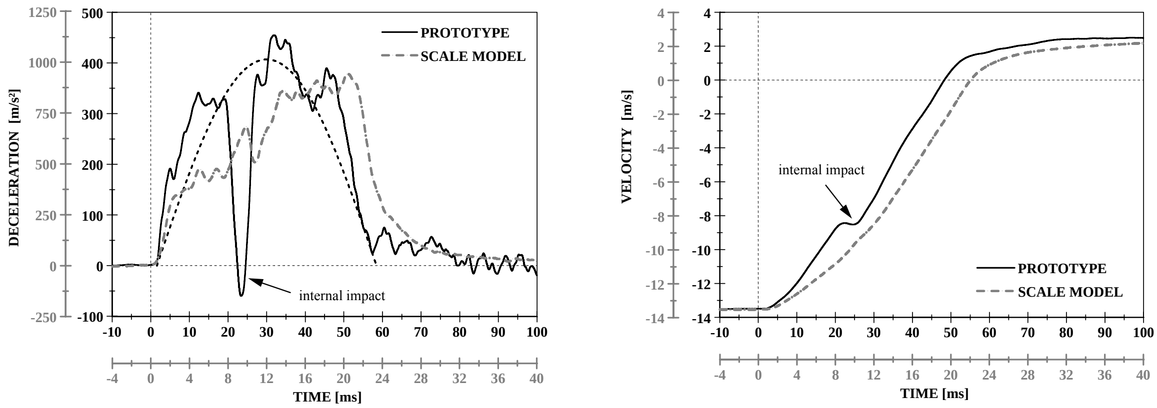

Figure 2. Vertical Drop. Deceleration and Velocity of Cask Body vs. Time.

rigid body motion vs. time of the prototype and scaled cask model in a 9 m vertical drop test. At first, visual comparison of the deceleration and velocity time curves identifies different chronological sequences resulting in characteristic values whose ratios differ from the applied scaling law. The basic characteristic of the prototype's rigid body deceleration can be described approximately as sinusoidal with a maximum value appearing at half the impact duration. However the model shows increasing deceleration over the impact duration with a maximum value at the end. The ratios $r(a_{max})$ and $r(\bar{a})$ for the maximum and average deceleration of the cask deviate to smaller values, while the ratios $r(d_{max})$ for maximum translation (≡ maximum shock absorber deformation) and $r(\Delta t)$ for impact duration deviate to higher values compared to the theoretical scale factors (see *Table 1)*. In regard to rigid body motion, the results suggest that, in general, the scaled cask model tends to represent the impact of the prototype model as softer. The reasons are found mainly in omitting the influencing phenomena of shock absorber behavior in the drop test scale model: see [R4].

Table 1. Vertical Drop Test. Rigid Body Impact Response of Cask Body.

Parameter	scale factor, *s*		ratio drop tests, *r*		deviation, *Δ*
max. translation, d_{max}	s_l	0.4	$r(d_{max})$	0.44	+9 %
max. deceleration, a_{max}	s_l^{-1}	2.5	$r(a_{max})$	2.10	-16 %
average deceleration, $\bar{a}$	s_l^{-1}	2.5	$r(\bar{a})$	2.05	-18 %
impact duration, Δt	s_l	0.4	$r(\Delta t)$	0.50	+24 %

Another effect, the significant change in deceleration causing a step in the velocity time history (see *Figure 2, right*) which occurs only during the impact of the prototype is notably obvious. This deceleration change indicates a delayed internal impact of the dummy fuel elements and basket on the inner side of the primary lid. Effects, reasons and consequences of interactions between cask and contents are discussed in [R5]. The internal impact causes a high temporary loading on the primary lid and its lid bolts, as appropriate strain measurements indicate. *Figure 3* shows the bending strain in the middle of the primary lid (*left*) and the axial strain of a lid bolt

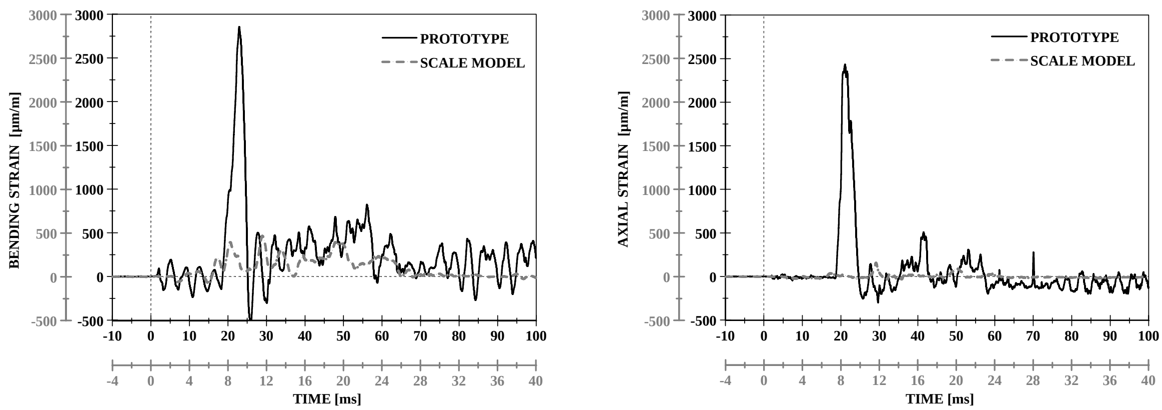

Figure 3: Vertical Drop Test. Primary Lid. Bending Strain and Axial Strain of Lid Bolt

(*right*) by comparing prototype and scaled cask model. The effect of the internal impact does not appear adequately in the scale-model, although the original existing gap between cask lid and contents/ basket is exactly modeled. Acceleration due to gravity plays a decisive role in relative movement and internal impact respectively: see [R5]. If the same material is used in prototype and scale-model, gravity effects are omitted. So, similar behaviour concerning internal impact is per se excluded - but not the effect in general. Furthermore, drop conditions -e.g. non-ideal position of contents or friction and adhesion effects- can reduce or eliminate the phenomena. The structural impact response reflects the above mentioned phenomena of the internal impact. The high stress of the primary lid as well as of the corresponding lid bolts due to the internal impact are omitted in the scale-model. The deviation of maximum axial strain in the flange region of the cask body (impact zone) shows again the softer impact behavior of the scale-model (see *Table 2*).

Table 2. Vertical Drop Test. Structural Impact Response.

Parameter (maximum value)	**scale factor, *s***		**ratio drop tests, *r***	**deviation, *Δ***
cask body; axial strain	1	1	0.74	-26 %
primary lid; bending strain	1	1	0.2	-80 %
bolt primary lid; axial strain	1	1	0.06	-94 %

The results underline the necessity to consider, in general, the effect of internal impact and the possibly significant high loading on the closure lid system affecting the leakage rate respectively. We cannot expect the effect to be simulated in a drop test using scale models. Therefore, for a few years BAM has required that the internal impact basically be assumed and considered in the safety analysis report for type B package approval.

<u>9 Meter Oblique Drop Test</u>

Visual comparison of the prototype and scaled model cask shows typical slap down impact behavior for both models: see [R6]. The rigid body motion behavior of the model is not similar but in a certain accordance with that of the prototype. After the primary impact of the bottom of the package, the package rotates thus causing a secondary impact to the lid side. *Figure 4* shows the measured lid sided acceleration signals of the cask body and the corresponding velocity-time curves. They demonstrate the acceleration of the cask's lid end during rotation from an initial velocity due to a free fall of 9 meters to a higher impact velocity and subsequent deceleration caused by the secondary impact. Both, prototype and scale model reach nearly the same impact velocity (see *Figure 4, right*).

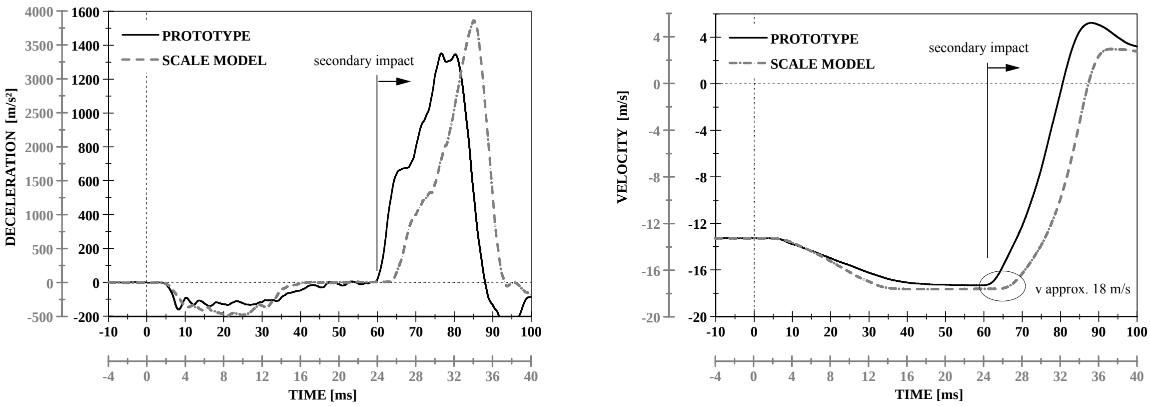

Figure 4. Oblique Drop Test. Deceleration and Velocity of the Cask Body (Lid Side).

Unlike in the results of the vertical drop test, the shock absorber in the oblique test tends to represent the impact of the prototype as harder in respect to scaling law. The ratio $r(a_{max})$ for maximum deceleration deviates to higher values, while the ratios $r(d_{max})$ for maximum translation and $r(\Delta t)$ for impact duration deviate to smaller values when compared to the theoretical scale factors: see *Table 3*. Thereby the shock absorber on the bottom side behaves significantly tougher than the one on the lid. Similarity is hindered notably because the shock absorber behavior reaches the hardening zone of the force-deformation function where the above mentioned strain rate effects are significantly high: see [R4].

Table 3. Oblique Drop Test. Rigid Body Impact Response.

Parameter	**scale factor**		**ratio experiment, *r***			**deviation, *Δ***	
				bottom	**lid side**	**bottom**	**lid side**
max. translation, d_{max}	s_l	0.4	$r(d_{max})$	0.28	0.37	-30 %	-6 %
max. deceleration, a_{max}	s_l^{-1}	2.5	$r(a_{max})$	2.93	2.61	+17 %	+5 %
impact duration, Δt	s_l	0.4	$r(\Delta t)$	0.37	0.39	-7 %	-3 %
impact velocity lid side, v	1	1	$r(v)$	–	0.94	–	-6 %

Structural impact responses show that the highest stresses occur for both, prototype and scale-model due to the secondary impact in the lid cask region facing the impact zone. Therewith highest stresses occur in the flange region of the cask body and the border area of the lids and their bolts. For this, *Figure 5* shows exemplarily the bending strain of the flange (*left*) and the

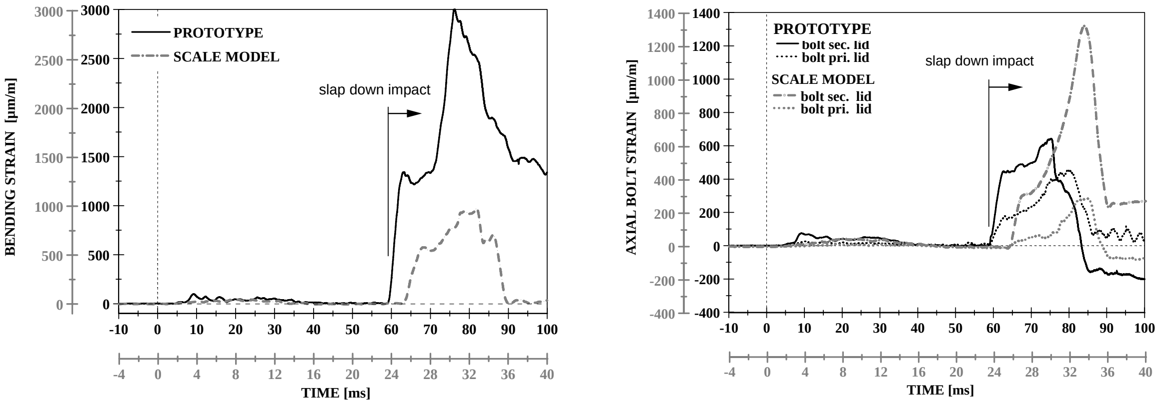

Figure 5. Oblique 9 m Drop Test. Strain History of Cask Body Flange and Lid Bolts.

axial strain of primary and secondary lid bolt (*right*) by comparing prototype and scale-model. Strain histories as well as single maximum values do not demonstrate similar behavior of the scale-model in the impact zone. Although maximum deceleration of the scaled model is higher, bending strain in the flange region and axial strain of the primary lid bolt is underestimated (see *Table 5*). Bending strain of the secondary lid and corresponding lid bolts is overestimated. This is

Table 5. Structural Impact Response of Cask Body, Lids and Lid Bolts.

Parameter (maximum value)	**scale factor, *s***		**ratio drop test, *r***	**deviation, *Δ***
cask body; bending strain flange	1	1	0.32	-68 %
secondary lid; bending strain	1	1	1.30	–
bolt, primary lid; axial strain	1	1	0.64	–
bolt, secondary lid; axial strain	1	1	2.07	–

probably a specific effect of grooves in the scaled test model lid for sensor cabling. The grooves have the same dimensions as in the prototype for technical reasons, which significantly reduces stiffness and results in more bending for the model. Therefore a comparison of this cask region in regard to similarity is limited.

1 m Prototype and 1.25 m Scale- Model Puncture Test

Comparison of scaled model and the prototype impact test data shows nearly similar deceleration time histories (apart from time shift) in phase 3 of impact (*Figure 6)* and correspondingly similar characteristic values (*Table 6*). The assumed reason is that the influencing phenomena of the wooden shock absorber no longer have any effect because of almost complete metal to metal contact between puncture bar and cask. This is quite different from the previous two phases where the puncture bar first punches the shock absorber's steel-shell (phase 1) and then perforates the wood inside (phase 2). However, the phenomena are reproduced by the scaled model in principle. Further analysis of the strain histories demonstrates that the rigid body

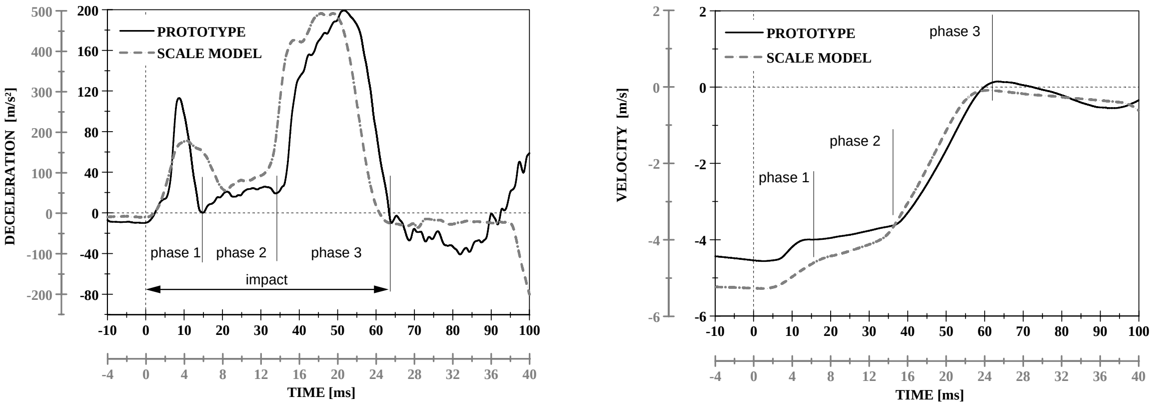

Figure 6. Puncture Drop Test. Deceleration and Velocity of the Cask Body vs. Time

Table 6. Rigid Body Impact Response of the Cask During Phase 3

Parameter	**scale factor**		**ratio experiment, *r***		**deviation, *Δ***
max. deceleration, a_{max}	s_l^{-1}	2.5	$r(a_{max})$	2.49	0 %
impact duration, Δt	s_l	0.4	$r(\Delta t)$	0.39	-4 %

response shows less scatter than the structural response. At first both prototype and scaled model show maximum loading in the cask body with lids and bolts localized directly at the impact zone of the package in time segment phase 3. The flange of the cask body is mainly loaded by bending strain in the axial direction with accompanying inward deformation and also bending strain in the circumferential direction (*Figure 7*). The time histories show a certain analogous but not similar behavior; the strain level of the model greatly undervalues that of the prototype (see *Table 7*).

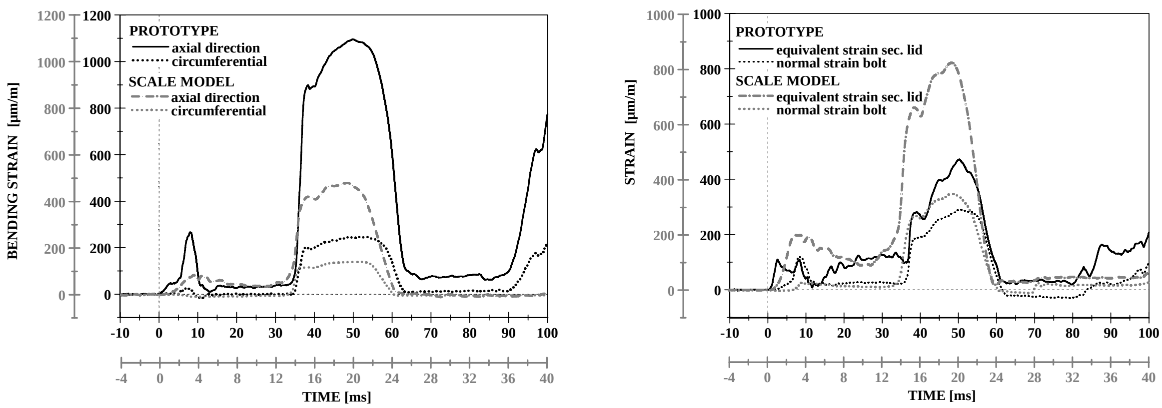

Figure 7. Puncture Test. Bending Strain of the Cask Body Flange (left), Equivalent Strain of the Secondary Lid and Axial Strain of Corresponding Bolt (right)

Looking at the equivalent strain of the secondary lid, the significantly higher strain of the model is probably due to the same specific effect of the lid grooves for sensor cabling as in the oblique drop test. The primary lid is almost unloaded in both models. The time history of the secondary lid bolts normal strain is quite similar (*Figure 7, right)* even if the level of the scale-model is somewhat higher (*Table 7*).

Table 7. Structural Impact Response of Cask, Lids and Bolts.

Parameter (maximum value)	**scale factor, *s***		**ratio drop test, *r***	**deviation, *Δ***
cask body; bending strain	1	1	0.46	-54 %
secondary lid; equivalent strain	1	1	1.70	+70 %
bolt sec. lid; axial strain	1	1	1.16	+16 %

CONCLUSIONS

In general, the comparison of impact test data shows that the structural response is mostly not similar and sometimes underestimated by the scaled model. The rigid body response often show less scatter than the structural response. One of the most relevant omitted effects is the internal impact of the contents on the primary lid in the vertical drop. The similarity of the impact response depends on the immanent limitations of the scaling model applied as well as many other influencing phenomena and effects through the experiments. The scale model cannot be expected to simulate all the influencing phenomena apart from the lack of their complete knowledge. However, the omitted effects must be identified and resulting possible errors taken into account when using the results determining existing safety margins. The results and conclusions presented are relevant for the design which was tested and cannot be considered as general guidance. Nevertheless, the results show that use of small-scale models needs a lot of additional investigations and calculations to cover all effects and cases to be considered in the safety analysis report. Small-scale model tests can sometimes only act as a benchmark for dynamic finite element calculations needed to assess the original design being approved.

ACKNOWLEDGMENTS

BAM thanks Mitsubishi Heavy Industries, Ltd (MHI) for the supply of specimens and the support in drop testing connected with collaboration in the BAM research project funded by the Federal Ministry for Education and Research under contract no. 02S8274.

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