EXPERIENCES AND PERSPECTIVES OF PACKAGE TESTING UNDER HYPOTHETICAL ACCIDENT CONDITIONS

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Contents of Presentation

1. Flashback to PATRAM 2004 Technical Tours
2. Package Testing to Environments Beyond Regulatory Test Standards (Germany)
   - Large Height Drops
   - Aircraft Crash Impact Simulations
   - Explosion Impacts
3. Experiences and Drop Test Campaigns at BAM
   - Metal Dual Purpose Spent Fuel and HAW Casks
   - Former small- and full-scale Casks Drop Testing
   - The new BAM Drop Test Facility
   - Actual Measurement Methods; recent Drop Test Programms
   - Thermal Testing (briefly)
4. Perspectives and specific Issues
   - Assessment Strategy
   - Problems of Scaling
   - Interdependence between Experiments and Calculations
   - Mechanical Testing of Packages with/without Impact Limiters
5. Concluding Remarks
Flashback to PATRAM 2004 Technical Tours

September 20-24, 2004
Berlin • Germany
Full-scale Drop Test
MSF-69BG
weight: 141 t
III.3 / 0995
24.09.2004
Drop Hight: 9m
10° slap-down
The BAM Test Laboratory in Front of the MHI-MSF Full-Scale Cask tested at the PATRAM 2004 Technical Tour-2 (from the left: Erhard Reeck, Thomas Quercetti, Thomas Reinke, Thomas Koehler, Karsten Mueller, Frank Burghardt, Mathias Minack, Heike Gruenewald, Oliver Kovacs, Tino Neumeyer, Peter Loewe)
200 m drop of a 1:2 model of spent fuel cask TN 8/9 onto reinforced concrete runway

(BAM, Meppen, 1977)
200 m drops with Pu nitrate package 18B
(BAM, Berlin, 1977)
25.5 m drop of a 1:3.4 scale model of spent fuel cask C-30 onto a concrete building (Brennstoffinstitut Freiberg, 1985)
19.5 m drop of full-scale spent fuel cask CASTOR Ic onto a highway target (BAM, Lehre, 1983)
900 m drops of GNS MOSAIK radioactive waste packages (1983)
14 m horizontal drop of CASTOR VHLW cask without impact limiters onto steel bars
14m drop test with the CASTOR VHLW cask with a 120 mm deep failure in the 260 mm ductile iron wall.
9 m horizontal drop
of CASTOR VHLW cask
with impact limiters
Numerical calculation of horizontal 9 m drop of CASTOR VHLW cask

Finite elemente model of cask with impact limiters

Dynamical calculation

See PATRAM 7007 presentation: L. Qiao, U. Zencker et al., 10/25/07, 2:00 – 5:00, Session E
Aircraft crash simulation test (WTD91, Meppen, 1977)

Simulation: Aircraft crashing onto a CASTOR®
Aircraft crash simulation test

Steel projectile (1000 kg, 300 m/s) impact onto the centre of a CASTOR IIa closure system (WTD91 Meppen, 1980)
Aircraft crash simulation test with a full-scale spent fuel cask
TN 1300 (WTD 91, Meppen, 1983)

Central impact onto protection lid
Impact onto cask wall
Post September 11, 2001 investigations of civil aircraft crashes onto interim storage sites

Side-on engine impact onto standing casks

Central impact of storage hall roof fragments onto the cask closure system

Fire
Side-on aircraft engine impact (after storage building wall penetration) onto upper half of a CASTOR V cask
Moving of the Casks after Aircraft Crash (0 … 1 sec.)
Impact of building roof fragments onto the centre of the closure system (G. Wieser et al., PATRAM 2004)
Finite Elemente Analyses of Casks in Fire Scenarios

BAM FE-calculation example:
Temperatures of a CASTOR cask with 40 kW spent fuel decay heat

**Balanced thermal conditions before fire**
- ≈80°C
- ≈300°C

**After 20 minutes fire duration**
- >500°C
- ≈300°C
- ≈400°C

**2 hours after end of fire**
- ≈300°C
- ≈350°C
- ≈250°C
Finite element calculation of a spent fuel cask's response to a blast wave due to a railway wagon (21 t TNT) explosion in 25 m distance (V. Ballheimer et al., PATRAM 2004)
BLEVE impact onto a CASTOR THTR/AVR spent fuel cask
(BAM, Horstwalde, 1999)
Fire test with a CASTOR THTR/AVR cask placed beside a LPG tank wagon
Cask movement after LPG tank wagon crash
Ir-192-capsule for Brachytherapy after impact test (ADR 2.2.7.4.5); length 3.2 mm, diameter 0.72 mm, wall thickness 0.05 mm.

Spent fuel transport and storage cask CONSTOR V/TC before 9 m drop test (ADR 6.4.17.2a); mass 181 t, length 7445 mm, diameter 3510 mm.
Dry interim storage of spent fuel and HAW in Germany in metal transport and storage casks

- First generation, central (AWR) storage sites -

• Gorleben (1983; HAW and CASTOR V 1995)
• Ahaus (1987; THTR/AVR 1992; CASTOR V 1997)
• Jülich (1993 THTR/AVR)
• ZLN Lubmin (CASTOR 440/84; 1999)
Dry interim storage of spent fuel and HAW in Germany in metal transport and storage casks

- Second generation, 12 at-reactor storage sites -

  - CASTOR V spent fuel casks
  - Licensed 2001 – 2003; built since 2002

Preliminary Interim Storage Facilities at 4 At-Reactor Storage Sites

  - CASTOR V spent fuel casks
  - Licensed 2002 – 2003; built promptly

First operating facility at NPP Emsland
The former BAM Drop Test Facility, Lehre

(max. Cask Weight 100 Tons)
Drop Tests with CASTOR Cask Models

CASTOR Ia-1:2

CASTOR IIa-1:2
Drop Tests with full-scale Spent Fuel Transport and Storage Casks

CASTOR Ia (1978)

CASTOR Ic (1983)

TN 900 (1985)

POLLUX (1994)
Transport package for fresh fuel assemblies  
- Slap-down 9 m drop -
1 m puncture drop test with 1:3 small-scale model of NCS 45 spent fuel transport cask
9 m oblique drop with 1:3 small-scale model of HAW transport and storage cask TN 81 (axis angle 5 °)
Drop tests with 1:3 small-scale model of HAW transport and storage cask TN 81
TN 85 Transport and Storage Cask for vitrified HAW (TNI)
Bird`s-eye View of BAM`s Drop Test Facility in Horstwalde
BAM Drop Test Facility Horstwalde
Construction of the unyielding IAEA Target
BAM Drop Test Facility Horstwalde

Unyielding Target
Steel reinforced Concrete Foundation:
14m x 14m x 5m
2,450,000 kg Concrete
103,000 kg Steel Reinforcement

Test Pad of Steel Plates:
10m x 4.5m x 0.22m
77,000 kg

See PATRAM 2007 presentation: K. Mueller et al., 10/26/07, 2:00 – 5:00 p.m., Session E
Steel Construction of Drop Tower and Test Hall

BAM Drop Test Facility Horstwalde

Detachment Device, BAM Design
- Hydraulic Rupture of a Steel Bolt
- Hydraulic Force: 5.500 kN
- Momentum free Release

200 ton Hoist
The new large BAM Drop Test Facility

Drop Tower with Test Hall

- Height: 36 m
- 200 ton Hoist,
  80 ton Portal Crane
- Test Hall with
  24 m x 20 m Area
Strain and Deceleration Measurements
Strain Measurements of Lid Bolts
Connection of the Measurement Cables
(CONSTOR 1:1 Cask)
Instrumentation plan of CASTOR® HAW/TB2 (1:2)

measuring points: 175
accelerometers: 23
uniaxial strain gauges: 16
triaxial strain gauges: 131
temperatur sensors: 5
max. channels: 128
Drop Testing
with corresponding deceleration time history

Multi-channel measuring devices

• Wideband differential bridge amplifier for direct connection of all bridge type devices
• Analogue bandwidth up to 200 kHz
• Sampling rate up to 10 MSamples/s each channel
• Resolution 12/16 bit
3D-Measurement

Gap between body flange and primary lid

Circularity of the primary lid
Close Range Photogrammetry

Measuring the relative lateral lid displacement
Deformation Measurements of Impact Limiters

Optical Surface Digitization Measurements

Deformed shock absorber model merged with cask data

Shape comparison with CAD data

Sensor arrangement with objects

Shock absorber deformation due to drop test damage
Helium Leakage Testing
Full-Scale Model
- Total Mass: 141,000 kg
- Length with Impact Limiters: 6,800 mm
- External Diameter of Impact Limiters: 3,100 mm

1:2.5 Scale Model
- Total Mass: 10,000 kg
- Length with Impact Limiters: 2,700 mm
- External Diameter of Impact Limiters: 1,300 mm
127 t MHI MSF 69 BG Full-Scale Drop Test (Sept. 2004)

9 m slap-down with 10° inclination

See PATRAM 2007 presentation: T. Quercetti et al., 10/24/07, 9:00 – 12:00, Session A
CASTOR HAW 28M Cask 1:2 Model

- Mass: 14.000 kg
- Length: 3.382 mm
- Outer Diameter: 1.415 mm
Drop Testing of CASTOR Cask Impact Limiter System (9m Corner Drop)
BAM Fire Test Facilities

Fuel Oil Pool

Propane Gas Fire Test Facility
Numerical Simulation of Cask Heating in a Fire

See PATRAM 2007 presentation: F. Koch et al., 10/26/07, 2:00 – 5:00 p.m., Session E
Strategy for Safety Assessment of Mechanical Accident Conditions (I)

1. Pre-test Finite-Element Calculations with the Package Design
   - for Justification of most damaging Drop Positions and Drop Test Sequences
   - for Identification of maximum Stresses and Deformations, to justify the Instrumentation Plan
Strategy for Safety Assessment of Mechanical Accident Conditions (II)

2. Performance of the Test Program with an extensively instrumented Package Specimen under Coverage with appropriate Measurement Techniques
Strategy for Safety Assessment of Mechanical Accident Conditions (III)

3. Verification of the Package Specimen (small- or full-scale Cask) Finite-Element Model

- Comparison with Test Results, considering real Test Specimen Properties
- Determination of most critical Stress Levels, Stress Intensities/J-Integral, Deformations
- Justify Model Simplifications
- FE Model Verification needs to be supported by Sensitivity Studies, Material/Component Testing to reach better Model Accuracy
Strategy for Safety Assessment of Mechanical Accident Conditions (IV)

4. Final Safety Analysis of the Package Design to be approved, using the verified FE Model
   - Determine max. Stresses, Stress Intensities/J-Integral, Deformations and compare them with relevant Material Properties, using appropriate Evaluation Concepts
   - Consider max./min. Temperatures, conservative Material and Geometry Specifications, max./min. critical Relations of other relevant Package Component Characteristics, Interactions, Reactions, Functions
   - Justify Package Design Safety $> 1$ regarding Safety against Failure due to Desintegration or undue Deformation
The Problem of Scaling
Aims of Drop Tests in View of Reduced-Scale Models

- Quantification of stresses and deformations
- Verification of calculations (methods, models)
- Identification of construction weak points

Use of Scale Models

- Quantification of stresses and deformations
- Verification of calculations (methods, models)
- Identification of construction weak points

- Safety demonstration
- Public acceptance improvement

possible and recommendable

problematic (additional investigations required)

not recommendable (better: full-scale)
Similarity and Scaling Laws

General Principles of Similarity

- Geometric Similarity
- Kinematic Similarity
- Dynamic Similarity
- Gravitational Similarity
- Material Similarity
- (Functional Similarity)

But: *It is impossible to consider all similarities in one model*

*Example:* Incompatibility of geometric, dynamic and material similarities with respect of impact time and strain-rate effects
“Functional“ Scaling of Closure Systems (I)

Metal Gasket ➞ Equivalent elastic decompression

And ➞ Equivalency of Flange Reaction
(Flange interfaces of the scale model and the original package shall relief under forces in a relation defined by scale laws.)

See PATRAM 2007 presentation: V. Ballheimer et al., 10/26/07, 9:00 – 12:00, Session A
“Functional“ Scaling of Closure Systems (II)
Elastomere Gasket ➔ Equivalent recommended O-Ring compression

And ➔ Equivalency of Flange Reaction
(Flange interfaces of the scale model and the original package shall relief under forces in a relation defined by scale laws.)
Similarity and Scaling Laws / Problem: Impact Limiters

Component Testing

Wood Characteristic Curve

Full-Scale Prototype Testing

Scale Model Testing

Problem of impact limiter modelling in calculations; lack of valid FE material laws

See: PATRAM 2007 presentation: M. Neumann et al., 10/24/07, 9:00 – 12:00 a.m., Session A

Dr. Bernhard Droste
Similarity and Scaling Laws / Problem: small-scale Model with soft Impact Limiter

Example: „1m puncture drop test“ in accordance to the IAEA regulations

Energy Similarity for Punch Impact onto Containment Boundary

\[ E_O = \lambda^3 \cdot E_M \quad \text{and} \quad \Delta E_O = \lambda^3 \cdot \Delta E_M \]

full-scale (1:1)
CASTOR® Ic

scale-model (1:2)
CASTOR® HAW TB2

See PATRAM 2007 presentation: F. Wille et al., 10/24/2007, 9:00 – 12:00 a.m., Session A
Drops of packages without their impact limiters; „inside“ handling accident drops

- Practical tests -

CASTOR Ic
13 m, Hexcel

COCON AVR
3.5 m, concrete

POLLUX, 5 m, concrete

TN THTR, 3.5 m, concrete
CASTOR® HAW/TB2: Storage Site Specific Accident Scenario
Test Specimen and BAM Finite Element Model
Code: ABAQUS/Explicit Version 6.5

See PATRAM 2007 presentation: H. Voelzke et al., 10/23/07, 2:00 – 5:00 p.m., Session E

Cask
219,838 elements
388,775 nodes

Target
110,136 elements
130,012 nodes

surrounding infinite elements
Conclusions for Safety Analysis - I -

**Small-Scale model drop testing and calculation** can be an essential part of mechanical safety assessment.

**But:** For small-scale testing it needs a lot of pre- and post-test calculations; calculations need to be verified based on drop tests. Both need material/component testing and transfer investigations to verify the original package response and its structural analysis completely.

**Full-Scale package drop testing** is more effective for complete package design verification, calculation verification and safety demonstration.

**But:** in case of large spent fuel and HAW casks (e.g. with more than 100 tons) it is nearly impossible to realize a complete drop test program with one specimen; some dedicated test positions/sequences have also to be accompanied by small-scale model, component and material tests as well as by calculations to cover all worstcase conditions. In this case also pre- and post-test calculations are necessary.
Conclusions for Safety Analysis - II -

The state-of-the art performance of reduced-scale and full-scale model drop testing needs extensive pre-test analysis, a complete test program with sophisticated measurement techniques and complex analyses to verify the original package design. For this purpose the Advisory Material for the IAEA Regulations should be extended and improved.

Quality assurance for the whole assessment process, and during laboratory manufacture operation has to guarantee the tested/approved package design status.

**A complete safety assessment needs a complex combination of all test methods:**

Small-scale and/or full-scale package testing, in combination with component tests, material tests, calculations and reasoned arguments to all critical regulatory and design conditions consider.
“Assessment Cube”

... if you cannot convince them ...
... confuse them ...

Dr. Bernhard Droste

PATRAM 2007, Opening Technical Plenary Session
THANK YOU
FOR YOUR ATTENTION