EVALUATION OF SAFETY OF CASKS IMPACTING DIFFERENT TYPES OF TARGETS

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SUMMARY

The paper presents results of the Phase 1 investigations of the joint German-UK research project "Evaluation of Safety of Casks Impacting Different Kinds of Targets" funded by the European Commission in order to improve safety and acceptance of radioactive materials transport. In addition to a literature survey concerning real target drop tests with Type B casks performed all over the world, the Phase 1 investigations had the primary objective to compare the loads of the casks during drops onto real (yielding) targets with those existing under IAEA test conditions. The paper gives a short description of the methodologic basis of these analyses and discusses first results. Because the project will be completed March 1998, only preliminary conclusions can be given in this written version (submission date October 1997). The oral presentation at the conference will cover the final results of the project.

INTRODUCTION

According to the IAEA *Regulations for the Safe Transport of Radioactive Material (1996)*, Type B casks for the transport of radioactive material shall be subjected to a 9 m drop test onto an unyielding target. For several reasons, information is of interest about the behavior of such casks if they drop onto real targets from greater heights and which margins of safety the casks have under these conditions. Investigations with regard to that problem were performed in the framework of a joint research project of the European Commission with participation of the Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin, Ove Arup & Partners Int., London, and Gesellschaft für Nuklear-Behälter, Essen. Calculations of BAM were also supported by the German Ministry for Environment, Nature Protection and Reactor Safety (BfS contract no. SR 2229/1)

The project consists of two phases. Phase 1 includes a literature survey concerning drop tests and analyses of Type B casks impacting real targets performed all over the world and the development and application of a methodology for determining the decelerations and impact forces for specified cask designs for a range of attitudes, targets and drop heights by simple calculation methods. The investigations of Phase 2 will be concentrated on the more exact calculation of stresses and strains in the cask components with finite element (FE) computer codes for two selected cask designs.

This paper presents outcomes of the Phase 1 investigations, especially, results of the literature survey and of analyses performed with the objective of comparing the different loads produced by drops onto unyielding and real, yielding targets.

BAM ACTIVITIES DURI NG THE 1ST PHASE OF THE PROJECT

Literature Review

In conformity with the division of tasks between the partners, the activities of BAM were concentrated on tests with casks in continental Europe. Because of missing publications about tests in this region outside Germany, the Interim Report of the project (*Droste et al., 1997*) summarizes only tests provided by BAM. In addition, results of tests with drop heights greater than the IAEA drop heights are described in a BAM research report, e.g., drops of a semi-scale model of the TN 8/9 spent fuel cask from a height of 200 m *(Schulz-Forberg and Hübner, 1980)*.

Applied Methodology for Casks with Wooden Shock Absorbers

According to the concept of the project, the objective of Phase 1 was to throw light on the differences between the unyielding (IAEA) target and real targets with regard to the loads of packaging components during transport accidents. Equivalent velocities or equivalent drop heights which cause the same decelerations of a package (i.e., the same maximum forces) in drops onto real targets as drops onto an unyielding target were accepted as a suitable criterion for assessments of real targets.

Because of the exclusion of stress analyses during the Phase 1 investigations, it was not necessary to model exactly the packaging and its components but it was more important to model the real targets characteristics and the characteristics of those components of the package which have really an influence on the package deceleration. The most important package components are the shock absorbers if typical Central European cask designs are considered. BAM decided to use for these analyses a mass-spring-model considering the shock absorbers and the target as two coupled springs. The model is described by *Droste et al. (1997)* in more detail. Using the well known dynamic deformation characteristics of the wooden shock absorbers (e.g, *Diersch et al., 1994*) which are mostly used in Germany, the problem remains to get force-deflection relationships of interesting real targets. Because of limited information about these model parameters, first calculations were focused on sandy and rocky soils. Especially for sandy soils, BAM could use their own results of investigations by *Holzlöhner* referred to by *Schneider and Jobst (1985)*.

The results of calculations discussed in this paper concern only drops onto the flat side of wooden shock absorbers. The reasons for this are, on the one hand, the concept of shock absorbers used by German packaging designers and, on the other hand, to consider firstly conditions with limited numbers of parameters having an influence on the maximum deceleration of the package. Moreover, it was the primary objective of these investigations to find out especially the qualitative relations between the properties of defined targets and the equivalent drop velocities. The equivalent velocity defined above can be estimated by the following equation:

$$v_R = v_B * \sqrt{1 + \frac{\int_0^{x_{T,max}} F_T(x_T) * dx_T}{m * g * h_B}}$$

The argument of the integral describes the energy absorption by the target considering the force F_T as a function of the target deformation x_T. The velocity v_B and the energy $E_B = m*g*h_B$ refer to the conditions in the case of the "basis" drop onto an unyielding target (index B). According to the definition of the equivalent velocity, it is assumed that the energy E_B must be absorbed by the shock absorbers also in a drop onto the yielding target. This assumption in a first attempt leads to rather conservative results of the calculations.

Both the maximum deformation of the target ($x_{T,max}$) and the maximum force $F_{T,max}$ (which equals at a drop onto an real target the force $F_{D,max}$) are results of the calculations considering the deformation characteristics $F_D(x_D)$ and $F_T(x_T)$ of the shock absorbers and the target, respectively. Both characteristics are shown in Figure 1. The deformation characteristic of sandy soil (curve 2) takes into consideration a weight density of 22 kN/m^3, a friction angle of 45° and foundation failure at a specified deformation (changing slope of the curve). In order to consider dynamic input conditions, the static value of the force at foundation failure was muliplied by a factor of 1.5.

Results of Analyses

The following conditions representing typical parameters of a spent fuel shipping cask were considered: mass of the package m = 134500 kg, diameter of the cask d_P = 2250 mm, effective thickness of the spruce-wood shock absorber s = 450 mm, diameter of the shock absorber (defining the contact area between the package and the target) d_D = 3070 mm.

The maximum values of the decelerations calculated for drops onto the unyielding (curve 1) and the real target (curve 2) are shown in Fig. 2. This diagram allows the estimation of the equivalent drop heights h_R (i.e, the equivalent velocities $v_R=\sqrt{2*g*h_R}$) for different "basis" values h_B. Similar curves would be obtained, e.g., for packages of the same mass but with a smaller diameter. The influence of important package parameters like the package mass and the diameter of the contact area of shock absorber (d_D) on the equivalent height is demonstrated by calculations whose results are shown in Figs. 3 and 4. For diameters d_D of 3 m (Fig. 3) and 2 m (Fig. 4) package masses of 20000, 100000 and 140000 kg were considered. The maximum deceleration during the 9 m "basis"-drop is the independent variable in these diagrams.

Figs. 2 to 4 are examples which illustrate the possibilities of simple calculations to find out qualitative and quantitative relationships between the equivalent velocitiy and the equivalent drop height, respectively, and the characteristics of real targets and geometric parameters of packages and shock absorbers. The problem is the supply of force-displacement relationships for real targets.

The results of these first calculations lead to some interesting conclusions. Wooden shock absorbers (with a low modulus of elasticity) are advantageous if one considers only the IAEA requirements, i.e., the drop onto unyielding targets: it is rather easy to keep the decelerations and the loads of the package components on a low level. On the other hand, the safety margins of containers with "weak" shock absorbers do not substantially differ if the loads during drops onto the unyielding and real targets are compared. This is demonstrated by the results of calculations performed here for sandy soil: The equivalent velocity amounts in that example to only 15.87 m/s. This corresponds to an equivalent drop height of 12.83 m compared with the 9 m "basis" drop height (Fig. 2).

In order to enhance the safety margins of shock absorbers for real targets it is more advantageous to use hard shock absorbers. As a consequence of this, the cask components have to withstand higher stresses during Type B tests. This example shows that the thickness of wooden shock absorbers would be a matter of optimization if real target drops shall be additionally taken into consideration. It should be only mentioned here that the "graceful failure" behavior of casks (owing to the safety margins implied by a limitation of maximum stresses, etc.) should be also considered then.

OVE ARUP ACTIVITIES DURING THE 1[ST] PHASE OF THE PROJECT

Literature review

A review of literature published on the topic of package impact onto real targets was carried out. Where possible the results of these studies were expressed as the ratio V_y/V_s and H_y/H_s where

V_y = velocity onto a yielding target which produces an acceleration equivalent to that from an impact onto an unyielding target at velocity V_s

H_y = drop height onto a yielding target which produces acceleration equivalent to that from an impact onto an unyielding target at drop height H_s

From simple mechanics it can be shown that $H_y/H_s = (V_y/V_s)^2$. The results are summarised in Table 1. However, it is important to note that both V_y/V_s and H_y/H_s are package dependent. And even for the same cask, the factor is different depending upon whether an shock absorber is attached or not, as shown in Akamatsu (1997). To judge the margin of safety purely by V_y/V_s or H_y/H_s ratios, the table above would prompt the erroneous view that the cask was safer without the shock absorber than with shock absorbers. Also as Holt (1985) shows the factor is impact attitude and drop height dependent. It is easy to overstate the mitigating effect of real targets in some instances, eg in the case of packages which are deformable relative to the target, in which case $V_y/V_s = 1.0$. Also, as Blythe et al. (1986) points out, in some rare cases it is possible to get $V_y/V_s < 1.0$ where the geometry of the package meets certain conditions. All these factors make communicating the mitigating effect of real targets to the Public a more complicated task.

Simplified Methodology for Casks with Integral Shock Absorbers

A hand calculation methodology for calculating the global response of casks with integral shock absorbers impacting real targets has been developed. The objective of such a methodology is that it can be used to obtain reasonably accurate information regarding overall response of casks in real target accident situations, e.g. acceleration and penetration, without having to resort to finite element analysis or other computational methods.

Previous work on the impact of casks with integral shock absorbers onto real targets has found that below a certain combination of target strength and impact velocity, the cask behaves as if it is rigid and only the target deforms. Above a certain combination of strength and velocity, the target behaves as though it is rigid and only the missile deforms. In between these two cases, both the target and the missile deforms. Two similar methodologies have been derived to deal with the two cases where either the target or the missile deforms. The case in which both the target and the missile deforms are not amenable to simple hand calculation methods and FE analysis is required. The methodology for a deformable target is presented here.

The methodology is based upon formulae derived from a simple theory of penetration, with “flow stress“ obtained by regression analysis of drop test data in *Holt (1985)* in which 84 drop tests of 10 kg missiles of four different simple nose shapes were carried out impacting a range of targets (from 20 MPa to 140 MPa) from a number of drop heights. The missiles were 1/16 scale based on their mass relative to a Magnox cask. The nose shapes tested include flat sided cylinders representing the area of a side of the Magnox cask, a symmetric wedge representing the edge of a cube and a symmetric three sided pyramid representing a corner of a cube. Acceleration was recorded for each test.

By consideration of forces at the contact surfaces between the missile and the target, the impact force, F, is given by:

$$F = A\,\sigma_f$$

where A = projection of the area of contact onto the original impact surface and has been assumed to be equal to the cross sectional area of the missile nose at penetration x

σ_f = flow stress of the target, value of which depends on the target's unconfined compressive strength, u, initial impact velocity, v, and missile geometry. It has been assumed in the methodology that it stays constant through the impact event.
It is expected to be higher than the unconfined compressive strength of the target material because of confinement and strain-rate effects, and its relation to compressive strength can be expressed as

$$\sigma_f = \textit{Flow Stress Multiplier (FSM)} \times u.$$

For a rigid missile of mass m, the maximum acceleration coincides with maximum area of contact and is therefore given by

$$\ddot{x}_{\max} = \sigma_f A_{\max} / m$$

Consideration of energy absorbed by the target during impact gives

$$E = \sigma_f P_{max}$$

where P_{max} is the volume of the crater, which can be approximated to the volume of the impactor truncated by a plane at height x_{max}.

Using the above equations and considering the geometry of the missile noses, the following relations of acceleration and flow stress have been obtained:

For cylindrical nose $$\ddot{x}_{maxc} = (A_c / m)\,\sigma_f$$

For wedge nose: $$\ddot{x}_{maxw} = v\sqrt{2l\sigma_f / m}$$

For pyramid nose: $$\ddot{x}_{maxp} = 3/2[\sqrt{3}\,\sigma_f / m\,]^{1/3} v^{4/3}$$

Regression analysis of the variation of peak and mean acceleration with target strength and impact velocity of the drop tests has been carried out by *Holt (1985)*. For this a polynomial in the following form have been used for σ_f

$$\sigma_f = k\,[\,g\,(\,K_1 + K_2V + K_3U + K_4V^2 + K_5VU + K_6U^2 + K_7U^3\,)\,/\,v^m]^n$$

where K_1 to K_8 are unknown constants; g is acceleration due to gravity; V is non-dimensionalised velocity defined as v/v_o; U is non-dimensionalised target's unconfined compressive strength, u/u_o; k, m and n are nose shape specific constants

K_1 to K_8 have been obtained for both peak and mean accelerations for all the nose shapes. From them, σ_f and FSM can be obtained. Variation of FSM for peak acceleration with impact velocity and target strength are shown in Figure 5 and 6 for the wedge nose and the cylinder nose respectively. Hence, for any combination of compressive strength and impact velocity, σ_f can be calculated and hence acceleration, penetration and impact force.

The steps in applying the methodology to estimate peak acceleration, maximum penetration and peak impact force of any cask with integral shock absorbers are as follow:

1. For the impacting geometry, impact velocity and target strength, obtain $\sigma_{f\ small\ scale}$, using the nose shape of *Holt (1985)* which most closely resembles (i) the impacting geometry and (ii) the condition of constraint under consideration.
2. Obtain $\sigma_{f\ full\ scale}$ by correcting $\sigma_{f\ small\ scale}$ for "size effects" using "size effect correction factor" C_m as follow:
   for cylinder: $\sigma_{f\ full\ scale} = \sigma_{f\ small\ scale} * C_m$
   for wedge: $\sigma_{f\ full\ scale} = \sigma_{f\ small\ scale} * (C_m)^2$
   for pyramid: $\sigma_{f\ full\ scale} = \sigma_{f\ small\ scale} * (C_m)^3$
   where $C_m = (16s)^{-0.227}$ and $s = (M_{full\ scale} / 48000)^{1/3}$
3. By consideration of the impacting geometry, derive the relationship between penetration distance, x, and volume of penetration, P, and area, A of the cask under consideration.
4. Calculate the volume of penetration from $[P = E / \sigma_f]_{full\ scale}$. Then penetration distance, $x_{full\ scale}$, and area, $A_{full\ scale}$ using equations derived under step 3.
5. Calculate the peak acceleration from $[\sigma_f A_{max} / M]_{full\ scale}$.
   Calculate the peak force from $[\sigma_f A_{max}]_{full\ scale}$

SUMMARY AND CONCLUSIONS

Preliminary results of a study funded by the EC DG XVII-C3 under Contract No. B4-1020/D/96-017 consist of a literature review of drop tests onto real targets carried out in the past and the development of simplified methodologies for the calculation of decelerations during such impacts. Two calculation methods have been developed, a mass-spring-model for casks with wooden shock absorbers and a missile penetration model for casks with integrated shock absorbers. In Phase 2 of the study, the stresses inside cask components will be further investigated by use of finite element methods to quantify the margins of safety in real target impacts.

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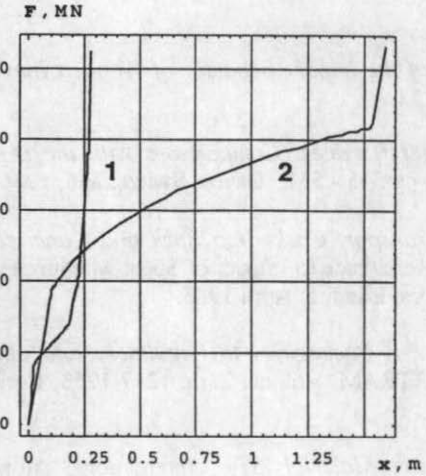

Figure 1: Flat drop of a cask equipped with wooden impact limiters;
Force-displacement curves for a spruce-wood impact limiter (1) and a sandy soil (2)

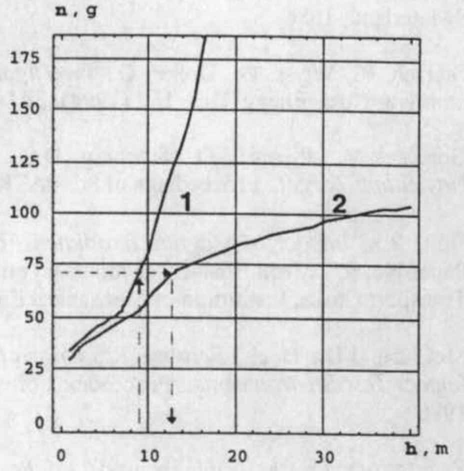

Figure 2: Flat drop of a cask equipped with wooden impact limiters;
Maximum decelerations during drops onto an unyielding target (1) and onto a sandy soil (2)

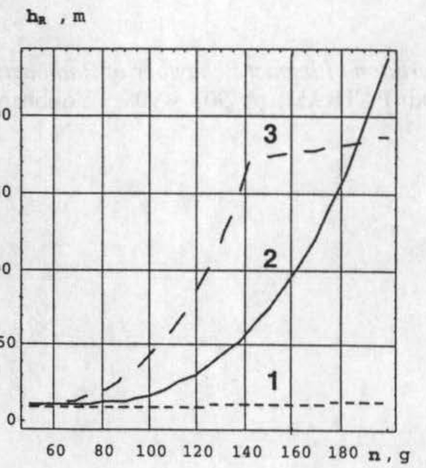

Figure 3: Flat drop of a cask equipped with wooden impact limiters;
Equivalent drop height for drops onto a sandy soil vs. maximum deceleration at a 9m drop onto an unyielding target; d_D=3m, m=20.000(1), 100.000(2) and 140.000kg(3)

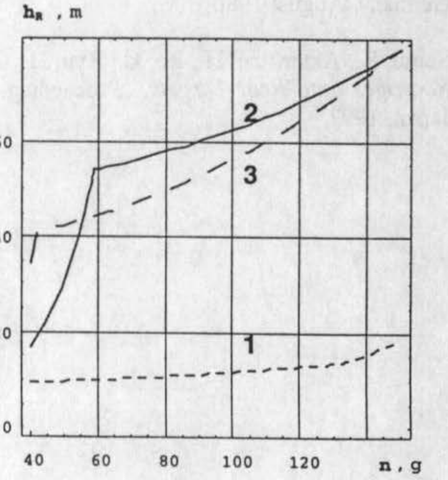

Figure 4: Flat drop of a cask equipped with wooden impact limiters;
Equivalent drop height for drops onto a sandy soil vs. maximum deceleration at a 9m drop onto an unyielding target; d_D=2m, m=20.000(1),100.000(2) and 140.000kg(3)

Source	Package	Target	V_y/V_s	H_y/H_s
McClure (1980)	LLD-1	Concrete	1.4	1.96
		Soil	2.3	5.29
	6M	Concrete	1.3	1.69
		Soil	2.4	5.76
	BE-83	Desert Soil	8.2	67.24
	20t Cask	Truck and Concrete Barrier	>2.8	>7.84
Holt (1985)	Magnox (lid corner, 9m)	50 MPa Concrete	2.55	6.50
	Magnox (lid corner,20m)	50 MPa Concrete	>1.86	>3.46
	Magnox (lid edge, 9m)	50 MPa Concrete	1.58	2.50
	Magnox (lid edge, 20 m)	50 MPa Concrete	>1.65	2.72
Gonzales (1986)	1/2 Scale cylindrical cask	Concrete	1.3- 1.4	1.69-1.96
		Soil	>2	>4
Shirai (1992)	48Y Cylinder	Uniform Concrete	1.0	1.0
		Concrete over hard soil	1.37	1.88
		Uniform hard soil	1.79	3.20
		Water	)	
		Uniform soft soil	)>1.79	>3.2
		Hard soil over soft soil	)	
Ammerman (1992)	90,700 kg Cylindrical Cask with Shock absorber	Hard Soil	1.93	3.73
	90,700 kg Cylindrical Cask without Shock absorber	Hard Soil	15.4	237
Akamatsu (1997)	TN-24 Cask with shock absorber	Unyielding Surface	1	1
		Asphalt Roadbed	2.38	5.67
		Concrete Roadbed	2.28	5.22
		Soft Sandy Soil	2.80	7.89
		Hard Sandy Soil	1.92	3.67

Table 1: Summary of Ove Arup's Literature Review Results

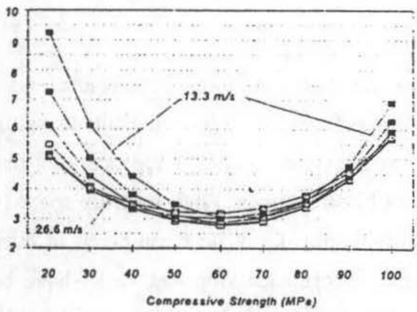

Figure 5. Variation of FSM for wedge nose

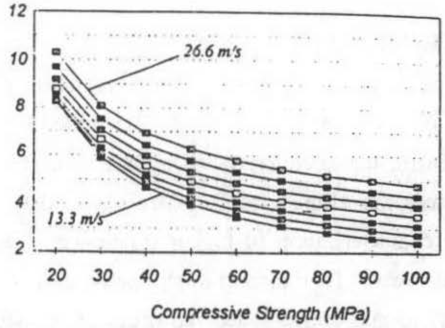

Figure 6. Variation of FSM for cylinder nose