Evaluation of the behaviour of the TK6 cask impacting real targets

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Introduction

Among other requirements for a Type B packages, the IAEA regulations require demonstration of its performance in 9m drops onto a flat unyielding target. Real targets are distinguished from unyielding targets in that a larger proportion of the drop energy can be absorbed by the target.

The work presented in this paper formed part of the research project *Evaluation of Safety of Casks Impacting Different Kinds of Targets*, carried out jointly by Federal Institute for Materials Research and Testing (BAM), Gesellschaft für Nuklear-Behälter mbH (GNB), and Ove Arup & Partners International Ltd (Arup), and funded by the European Commission (Project EC-DGXVII/C/3.

The work consisted of the following components:

1. literature survey of tests and analyses of package drops onto real targets;
2. development of a "simple" methodology for determining "global" response - decelerations and impact forces - for drops onto flat real targets.
3. detailed evaluation of cask response in drops onto flat real targets using finite element methods.

This paper presents the work carried out by Arup in Component 3 - to evaluate - using finite element modelling in LS-DYNA - the detailed impact response of the TK6 cask in drops onto flat real targets, to examine both the global response (e.g. impact force, acceleration, target penetration etc) as well as local responses (e.g. bolt stresses, seal gaps, local interaction between cask and target etc), and to compare the response with drops onto an unyielding target.

Selection of cask for the evaluation

In terms of design philosophy for energy absorption and deceleration control in drop accident scenarios, spent fuel casks can be broadly classified into one of two categories:

- Casks which rely on plastic deformation / metal flow of integral parts of the cask to absorb energy and control deceleration - e.g. the Russian TK6 cask and the Magnox cask, or
- Casks which rely on impact limiters with energy absorbing material in-fill (e.g. wood) to absorb energy and control deceleration - e.g. CASTOR casks

Impact behaviour of these two types of casks in drops onto unyielding targets and onto real targets are fundamentally different. So, a representative cask from each category was evaluated in Component 3 of the overall programme. GNB carried out the detailed evaluation using the MOSAIC cask, which belongs to the second category. Arup used the Russian TK6 cask, which belongs to the first category.

The TK-6 cask is a Type B package to transport spent VVER-440 fuel from nuclear power plants in Russia and Central and Eastern Europe to the reprocessing facility at Chelyabinsk. Each cask can carry up to 30 fuel assemblies and the maximum all-up weight of the cask is 92 tonnes. The cask consists of an electroslag welded forged steel body and a forged stainless steel lid which provides shielding and containment. The lid is attached to the body by means of 24 high strength bolts, and containment at the joint is provided by a rubber seal. Fins are attached to the outside of the cask to facilitate dissipation of decay heat. The lid is chamfered on two opposite sides, over a length of perimeter which includes four bolts each.

Arup had carried out a comprehensive safety evaluation of the package for the European Commission TACIS programme, which included evaluation of its performance in the IAEA drop accident scenarios. A detailed finite element model was built and was analysed for the critical drop orientations. The model was validated as part of the work and its performance in accurately simulating the impact behaviour of the cask was ascertained.

Selection of targets for the evaluation

In order to gain confidence in the analysis prediction of the impact behaviour of TK6, it is necessary first to verify that the model of the target is robust and simulates reality accurately. One way is to benchmark the target model with physical tests - either material tests of the target material under the correct loading conditions, or better still, drop tests onto the target with the target also characterised.

The work done by A Gonzales [1] in 1987 satisfies the latter criterion. Gonzales carried out a comprehensive experimental testing program to compare target response of a number of targets to an axis vertical drop of a simple model transportation cask from various drop heights. His targets included a native desert soil target, a concrete runway target, a concrete highway target, an imported borrow target and an unyielding target. On the first three targets, three drop tests were carried out from three different drop heights - 9, 21 and 36m. Whereas for the last two, drop tests were carried out from one drop height. Deceleration time histories, impactor deformation, target behaviour and target penetration were all measured. For some targets, a variety of material tests were also carried out to characterise the material properties.

Among the four targets, native desert soil and concrete highway targets were chosen to be the targets for the present study, for the following reasons:

(1) The native desert soil represents a realistic target with a lower bound target strength and the concrete highway target is a realistic target likely to be encountered in transport and it represents a layered target which is not amenable to the simple calculation methods developed in Component 1.
(2) Drop tests were carried out at a range of drop heights for these targets, hence allowing benchmarking of the model against more than one loading scenario, hence improving the confidence of the benchmarking, and
(3) Amount and quality of information provided on test results and material properties is better for these two targets than for the others.

Selection of drop scenario for the evaluation

Analyses of drops of the TK6 onto an unyielding target indicated that the worst impact attitude is the lid edge orientation with the trunnion on the plane of symmetry. This attitude produced the most critical combination of bolt loading and the biggest lid-to-body gaps. This attitude was adopted for the present work.

Regarding drop height, in order to allow a direct comparison with the regulatory 9m drop onto unyielding target, the cask was analysed for 9m drop onto both the native desert soil target and the concrete highway target. And to allow a comparison of global response between drops from different drop heights onto the same target, a 36m drop was also analysed for the concrete highway target, with the TK6 modelled as 'rigid'. The overall matrix is summarised in the table below

Target Type	9 m lid edge	36 m lid edge
Unyielding	✓	
Concrete highway	✓	✓
Native desert soil	✓	

Benchmarking of target model

For both the native desert soil target and the concrete highway target, the target model was benchmarked against two drop heights used by Gonzales - the highest, 36m and the lowest, 9m.

The impactor used by Gonzales represented a simplified half-scale truck transportation cask. It weighed 2.4t and measures 0.5m diameter by 1.8m long. It's contents were attached to the body in such a way that the whole unit was essentially a solid mass. Since the test unit did not suffer any permanent deformation in any of the four tests selected for benchmarking, and that target deformation was far larger than any elastic deformation of the cask, it was modelled as rigid in the benchmarking analyses.

The soil target used by Gonzales was in-situ at the test facility. A series of laboratory and on-site tests were performed to characterise its properties, including compaction, density, moisture content, sieve analysis, triaxial, unconfined compression, confined compression and consolidation.

A Drucker-Prager material model was chosen to model the soil target. The material model is often used to model granular materials which exhibit pressure dependent yield. It uses a smooth Mohr-Coulomb yield surface, associated inelastic flow in the deviatoric plane, and separate dilation and friction angles. Input parameters were derived from material test data presented by Gonzales, and the data define the shape of the yield and flow surface in the deviatoric plane as well as the friction angle. The parameters are summarised as follows:

Layer no	Depth (mm)	Density (t/m^3)	Shear Modulus (kN/m^2)	Poisson's Ratio	Cohesion (kN/m^2)	Angle of Shearing resistance (°)
1	0-610	1.66	4620	0.25	20.54	34
2	610-910	1.82	6350	0.25	41.08	28
3	910-1220	1.88	5180	0.25	31.04	28
4	1220-1520	1.86	4990	0.25	27.59	27
5	> 1520	1.86	4990	0.25	27.59	27

A particular phenomenon associated with the large penetration in the 36m drop of the impactor vertically into soil, is the punching action which detaches the soil immediately in front of the impactor from the surrounding soil by shear. There are two alternatives for modelling this phenomenon: 1) to define shear failure surface explicitly – to reflect reality, or 2) to let the solid elements and the material model deal with the shearing failure. The problem with the first option is how to justify the parameters especially the coefficient of friction in modelling the failure plane. Although the second option is more robust, it has a potential problem with numerical instability – as elements around the shear plane distort significantly.

In the 9m drop analysis, the problem was not as significant as the penetration was smaller, and the definition of a failure plane was not strictly necessary. Nonetheless the 9m drop analyses were carried out using both target models to assess the effect of the coefficient of friction (n) and to justify the value of for the 36m analyses.

Figure 1 shows a comparison of the acceleration–time history of the cask from the test and from the analyses. All the acceleration traces show the same trend as the measured one and show overall good correlation - an initial peak followed by a more or less constant deceleration. The acceleration trace from the analysis with n=0.2 correlates best with the measured acceleration trace, whereas the acceleration trace from the analysis with n=0.9 overestimates the acceleration after the initial peak. The predicted penetrations were within 15% of the measured value. All the analyses matches well with test in terms of overall timing. Stress and displacement distribution in the target was also sensible and as expected.

For the 36m drop, acceleration-time history from analysis correlates very closely with test, also with coefficient of friction of 0.2. Target penetration obtained by analysis also matches well with the value measured from test, differing by only 9%.

Gonzales' concrete highway target consists of a 12 in layer of compacted native soil, which underlies a 9 in layer of compacted crushed quarry stone, then surfaced by a 9in thick concrete slab.

However, the material properties given were not sufficient for deriving the input data for detailed modelling of the target. Instead, it was decided in conjunction with BAM, that a 'concrete highway' set-up based on the German Highway design criteria - which is similar to the Gonzales concrete highway target - should be used. It was agreed that an overall comparison with the original Gonzales test was still possible although the possible differences in the target properties should be taken into account.

The revised 'concrete highway' material properties are given in the table below, with Layer no 1 being the concrete slab, Layer no 2 the gravel layer and Layer no 3 the underlying soil base.

Layer no	Thickness (mm)	Density (kg/m^3)	Young's Modulus (MPa)	Poisson's Ratio	Internal Angle of Friction (°)	Cohesion (MPa)
1	200	2200	34,000	0.2	-	35 (UCS)
2	300	2200	200	0.3	60	0.5
3	> 300	2000	20	0.5	30	0.0

A Drucker-Prager material was adopted to model of the gravel layer and the underlying soil base. The LS-DYNA Material_Soil_Concrete was used to model the concrete slab.

Figure 2 shows the deceleration of the impactor for the 9m drop analysis. It exhibits a two-phased behaviour as can also be seen in acceleration trace from the test - the initial high deceleration phase corresponds to the resistance of the concrete slab, followed by cracking and formation of a conical shear plug; and the second phase of the deceleration process with its lower but constant deceleration corresponds to the deformation of the underlying gravel and soil which are considerably softer than the concrete layer. The correlation between the predicted trace and the Gonzales measured trace is surprisingly good considering that the two concrete targets may have different material properties and slightly different geometries.

For the 36m drop, although comparison could not be made with acceleration-time history of the test because of a problem with the test data, penetration predicted by analysis fell within 10% of the measured value.

Correlations between tests and analyses for both targets provided the confidence that the target models were sufficiently accurate in predicting the behaviour of the targets.

Modelling of the TK6

The model of the TK6 was designed so that impact behaviour of the cask can be evaluated at both the global level - in terms of overall structural integrity, and in the local level - estimation of the size of lid to body gaps, which are typically less than a millimeter.

The model is shown in Figure 3 (with cut-outs to show the interior of the model). It consists of approximately 200,000 elements. The mesh in the region of the lid-body interface is refined to ensure deformations in this region can be accurately simulated.

Detailed modelling of the TK6 impacting the real targets

The target models and the TK6 models were then combined, together with the correct boundary conditions, to analyse the 9m and 36m drops onto the concrete highway target, and the 9m drop onto the native desert soil target.

Results

Deformation in the target in the 9m drops and the 36m drop together with contours of hydrostatic pressure (defined as $(σ_1+ σ_2+ σ_3)/3$) are shown in Figures 4 and 5 (note: different contours are used in the three figures). The deformed shape of the target in all three cases are very realistic - with the cask making an imprint onto the target and with features of the cask clearly identifiable in the imprint. In the concrete highway target, the pressures are higher due to the higher strength in the concrete slab than in the corresponding top layer in the native desert soil target. The higher pressures correspond to the sharper corners of the cask surface, such as the bolt heads, the three shock-absorbers and the trunnions, as they bear onto the concrete slab and cracks it. The pressure in the native desert soil target is more evenly distributed, as the top layer of the soil offers a lower local resistance to the cask components coming into contact with it than the concrete slab in the concrete highway target, hence a more uniform interface between the cask and the target as the cask penetrates into the target.

Von Mises stresses in the lid and body of the cask and in the bolts in the 9m drop onto the concrete highway target are shown in Figure 6. The highest stresses are found in the heads of the long bolts nearest to the initial point of impact and the shock absorbers as they bear onto the concrete and cracking it. The loadings on the bolt heads then transmits onto the lid around the bolts holes producing the locally high stresses. However, the maximum stresses in the cask in the 9m drop onto the concrete highway target and the native desert soil targets were considerably below the yield stress of the cask material.

Comparison of response - real vs unyielding targets

The table below presents a summary of the key numerical results from the four analyses.

Target	Unyielding Target	Concrete Highway Target		Native Desert Soil Target
Drop height	9 m	9 m	36 m	9 m
Duration of event	15ms	140ms	200ms	180ms
Peak Acceleration	180g	12g	48g	11g
Target Penetration	0m	1.2m	2.2m	1.45m
Max Impact Force	174MN	19MN	30MN	11MN
Max Force on the Lid	15MN	2.5MN	-	3.0MN
Max Lid-Body Gap	0.85mm	0.12mm	-	0.1mm

Peak acceleration from the drop onto the unyielding target is approximately 15 times the value from the drops onto either of the real targets from the same height, with the event timescale a tenth of the drops onto the real targets. In the case of the unyielding target all the energy needs to be absorbed by the cask itself and there was considerable crushing of the shock-absorber and of the lid in the proximity of the impact. The real targets analysed are "soft" compared with the cask material and the kinetic energy of the cask is absorbed almost entirely by the deformation of the target. It absorbs energy slower than the cask's material, hence large target penetration and long event duration.

Comparing results from the two real target, the peak acceleration is marginally higher in the concrete highway target, and the corresponding target penetration is slightly smaller. The 'concrete highway' rt soil' target in that the properties of the underlying soil layers are quite similar. The significant difference is the presence of the concrete slab and the gravel layer in the concrete target. Once the concrete is cracked, it loses its load carrying capability and resistance to the cask was then provided by the underlying soil.

Although the initial kinetic energy of a 36m drop is four times that of the 9m drop, the predicted peak acceleration for the 36m drop was only a quarter of the value of the 9m drop onto the unyielding target.

In terms of stress, the TK-6 did not suffer any plastic deformation in the drop onto the real targets.

In terms of lid-body gap, the largest gap in the drop onto unyielding target was predicted to be 0.85mm while in the real target impacts, the gaps are not expected to be larger than 0.1 mm.

Conclusions

In the combination of cask design and target type analysed, the difference in response in drops onto unyielding and real targets is significant. The targets analysed were 'soft' compared with the cask, and the majority of the energy absorbed by the target, with no permanent plastic deformations in the cask. Peak accelerations and impact forces in real target impacts were shown to be less than 10% of the values obtained from the drop onto an unyielding target from the same height. And dropping four times as high as the regulatory drop height onto the concrete highway target, resulted in a deceleration a fourth of the regulatory 9m drop onto an unyielding target.

The work has shown quite clearly the capability of finite element technique in modelling these impact scenarios realistically, and providing information beyond what can be gained from drop tests in understanding the behaviour of casks. It is recommended that finite element analysis be used as a tool to demonstrate the real margin of safety of casks.

It has been found that there is a general shortage of information of the behaviour of real targets in the loading regimes of relevance. It is recommended that drop tests (with 'variables' including targets, casks, drop heights, and drop orientations), with material characterisation and finite element analyses be carried out to further quantify the real safety margin of casks and to obtain a more robust understanding.

References

[1] Gonzales A, *Target Effects on Package Response: An Experimental and Analytical Evaluation*, SAND86-2275, May 1987.

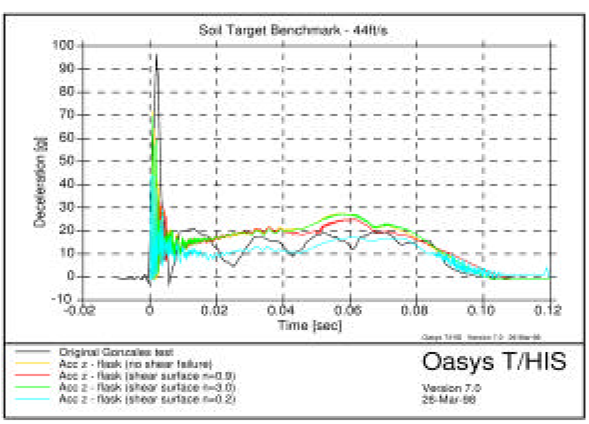

Figure 1: Native desert soil benchmark:
9m drop: test-analysis correlation

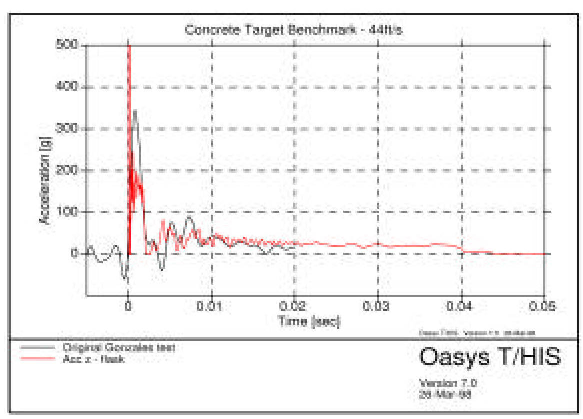

Figure 2: Concrete highway benchmark:
9m drop: test-analysis correlation

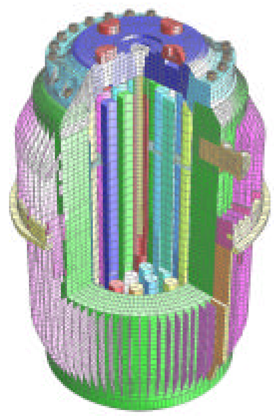

Figure 3: Finite element model of the TK6

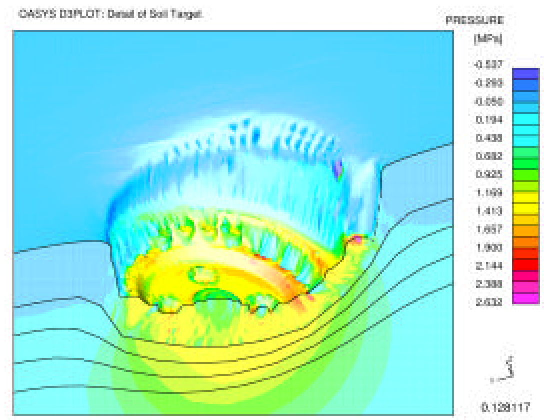

Figure 4: Native desert soil target: 9m drop: target deformation

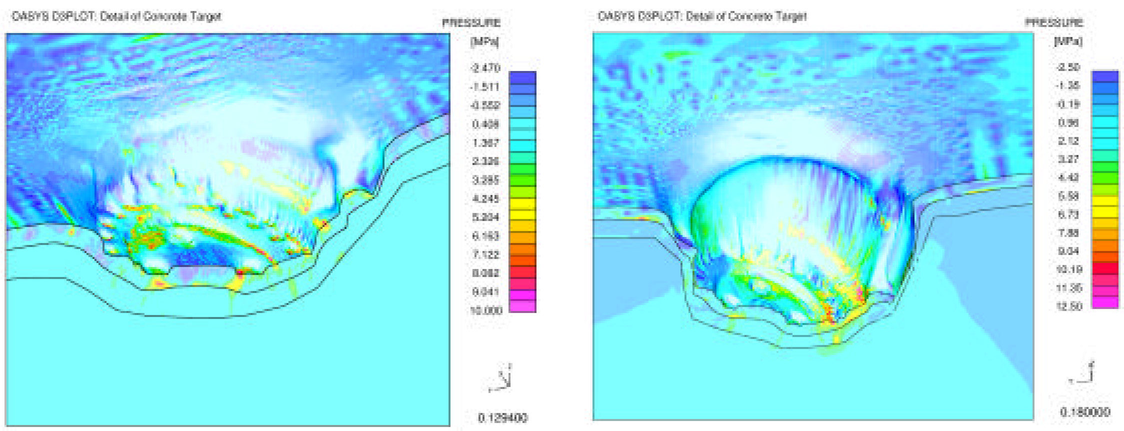

Figure 5: Concrete highway target: 9m and 36m drop: target deformation

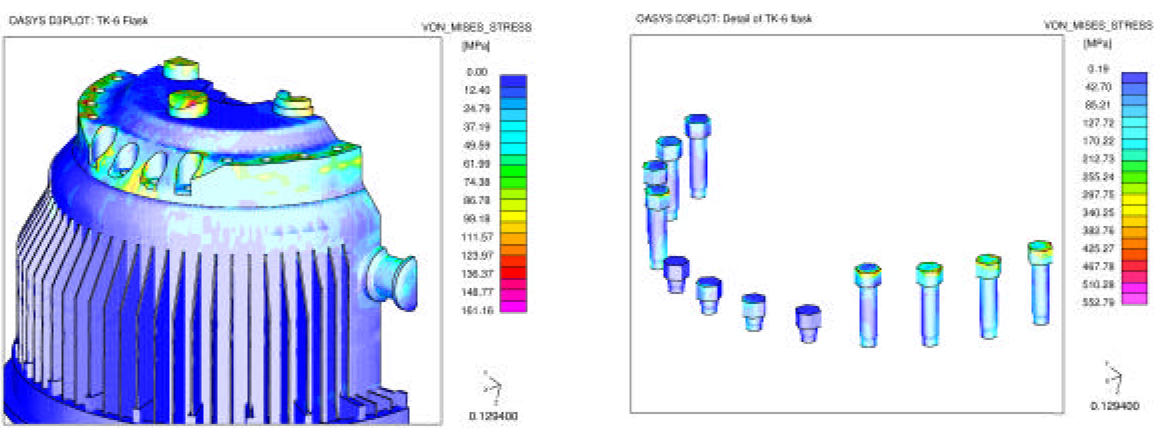

Figure 6: Concrete highway target: 9m drop: Cask and bolt stresses