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NUMERICAL ASSESSMENT OF SPENT FUEL CASKS IMPACTING ON REAL TARGETS

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Abstract — A reference container of high capacity was analysed for loads beyond those it has to withstand during a 9 m IAEA drop test onto an unyielding target. In doing this a lid-end drop with shock absorber onto a real target was simulated. This is a possible accident for the rail transport of such casks. In this case the most critical components of the containment system are the primary lid bolts. The behaviour of the lid system and its sealing function were investigated with finite element (FE) analysis. To correlate the findings with a corresponding impact velocity onto real targets an analytical method was used. Despite the conservative assumptions made in this study a two-fold safety factor compared to the 9 m drop tests onto the unyielding target could be shown. The quantification of the additional safety the cask might provide requires further basic investigations on the behaviour of the real targets considered as well as the reduction of the conservatism included in the assumptions made up to now.

INTRODUCTION

Type B packages certified for the transport of radioactive materials meet the requirements of the IAEA Regulations. By subjecting the casks to the cumulative effect of a sequence of mechanical and thermal tests it is ensured that the containers survive even the heaviest accidents in a way that neither an illicit release of radioactivity occurs nor ionising radiation exceeds the admissible values. Beside others, the 9 m drop onto an unyielding target belongs among these tests. However, drops from substantially greater height or with higher impact velocity onto real (yielding) targets are conceivable in real accident scenarios. Previous investigations on the relation of drops onto real and unyielding targets showed that due to the massive construction of the spent fuel transport containers and also to the absorption of a part of the total drop energy by the yielding target, a multiple of the impact velocity observed in the 9 m IAEA drop test onto an unyielding target is covered. This general statement has to be verified for current types of high-capacity container constructions, e.g. large transport and storage casks[1,2]. This article describes the work carried out for the investigation of the stressing of the impacting cask (especially lids and sealing system) as a function of impact velocity and target resistance for a reference container representing these high-capacity designs.

The reference cask (overall mass 134.5 te) is a monolithic, cylindrical, ductile cast iron container with a double lid system. It is also equipped with impact limiters (diameter approx. 3 m), which cover the top and bottom ends and also parts of the side wall of the cask and are filled with wood as energy absorbing material.

During rail transport of such containers various accident scenarios are conceivable. Since no sufficient statistical data for ranking different categories of accident by their probability were available at the time the decision on the accident scenario to be studied had to be made, it was decided to examine the impact onto the ground surrounding the track (e.g. the drop from a bridge onto the underlying ground). The characteristics of the ground were varied for the different calculations to cover a spectrum of real targets.

The determination of the most critical parts which afterwards have to be analysed in detail is only possible for a specific load case, which here means a specific drop orientation. For this reason a head-on impact onto the flat surface of the lid-end shock absorber (Figure 1) with the primary lid bolts as the critical component was chosen. In this case real targets show their maximum penetration resistance, compared with other drop orientations, due to the large initial contact area of the flat end of the reference cask's shock absorber. Furthermore in the region of the primary lid seal even small deformations of the bolts could lead to an impairment of the containment of the otherwise thick-walled cast iron container. Since the design of the lid area inhibits significant radial displacements of the primary lid, oblique or horizontal drop orientations cannot exert loads onto the bolts leading to failure by shear. Thus the vertical drop orientation is the most critical for the bolts because the possible displacement of the primary lid is significantly larger in the axial direction.

The complex problem of examining the cask's behaviour in such an accident was divided into the following sub-tasks, which were examined independently of each other using suitable methods for each specific question:

(1) Detailed inspection of the behaviour of the internal (primary) lid, its bolt connection and the sealing function under accident loads up to the failure of the lid bolts.
(2) Investigation of the system of the secondary lid/shock absorber for determination of the energy absorption during the impact and the possible interaction of both lids.

(3) Investigation of the resistance behaviour of real targets under the impact load.

For the finite element analysis presented in the following sections the package ABAQUS[3] was used. Furthermore for the investigations of the impact deceleration onto real targets the program 'Mathematica'[4] was used.

INVESTIGATION OF THE SEALING FUNCTION OF THE PRIMARY LID

The primary lid and the built-in metallic seal together with the cask body form the containment system for the inventory. In mounted state the steel lid disc and the cask body are firmly bolted together. In order to examine the deformation behaviour of the primary lid sealing system, a FE model was implemented. It consists of isoparametric, three-dimensional, cubic continuum elements with linear interpolation and complete integration. Due to the symmetrical structure the model is limited to one of the overall 48 bolts and the appropriate sectors of container and lid (Figure 2). The primary lid is formed by a staged disc. Further simplifications are made by modelling the bolt as a smooth, cylindrical shank and a solid cylinder on top to represent the bolt-head. Besides the limitation to an appropriate sector, the modelling of the cask body is limited in the axial direction but long enough to hold the drilling for the attachment of the bolt shank without influencing the result. The seal as well as the gasket groove are not included in the model. The behaviour of the seal is determined on the basis of its load-deflection function. The displacement of the nodes on the symmetry planes is restricted in the tangential direction; on the bottom surface of the container sector the nodes are fixed in the axial direction. The bolt which connects lid and container has its shank fixed in the drilling of the container. Between the bolt's head and the lid contact with friction is used. This kind of contact is also defined between lid and container.

The primary lid and bolts are made from steel, the container body consists of ductile cast iron. For these

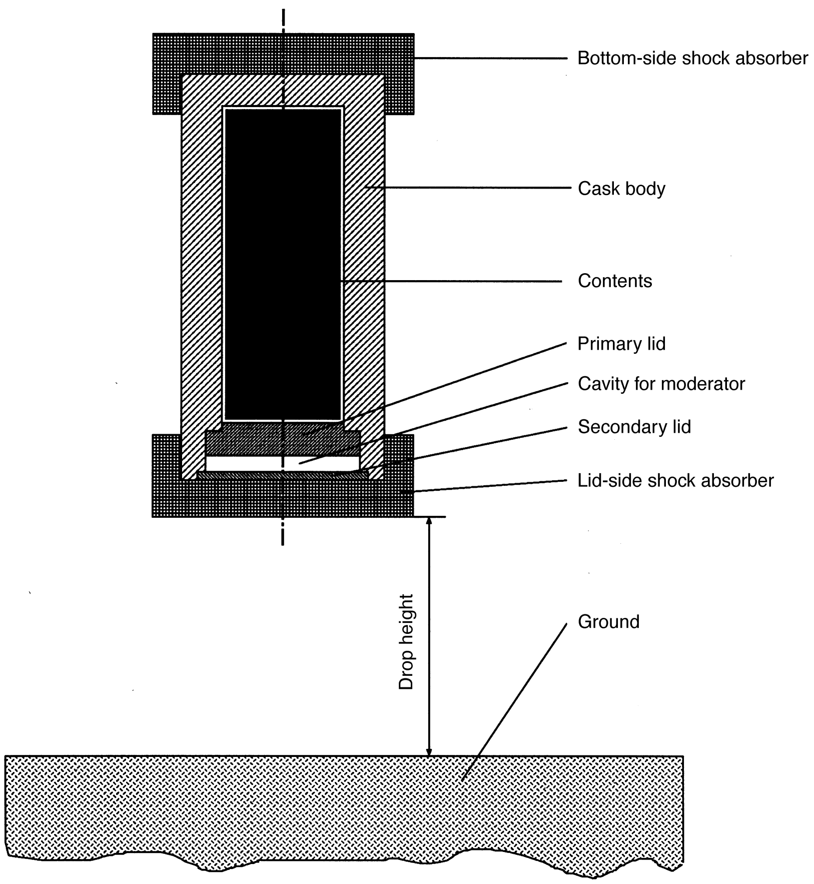

Figure 1. Illustration of the accident scenario studied.

components an elastic–plastic material law with a v.-Mises yield condition and isotropic hardening was used. The constitutive parameters were taken from common standards or material data sheets[5,6]. As value for the yield stress, 90% of the proof stress indicated for the material were used ($R_e = 0.9R_{p0,2}$).

With a special option of the FE program used a pretension is applied to the primary lid bolt. This is only possible with the implicit version of the program and makes a static analysis of the problem necessary due to the strongly increased cost of computation for an implicit dynamic calculation.

In the static simulation the behaviour of this structure was investigated under the action of loads arising out of a maximum impact deceleration. Hence the model is exposed to gravitational forces by equating the gravity constant to the magnitude and direction of this deceleration. Additionally to the gravitational forces of the model, the gravitational forces of the contents (assumed totally rigid) are applied as force per unit area on the inner side of the primary lid in conjunction with the maximum admissible positive pressure in the container. After simulation of the behaviour under maximum load the gravity is removed to get the unloaded state of the permanently deformed system.

To determine the behaviour of this system, calculations for a wide range of decelerations were performed up to the hypothetically assumed failure of the primary lid bolts. Failing of the bolts is assumed to occur when the force to which the bolts are subjected exceeds the force which leads to failure of a bar with equal cross-sectional area in a static tension test. For the bolt's material an ultimate tensile strength of 780 MPa is used.

The average tensile stress in the bolt, calculated using the cross-sectional area of the undeformed bolt, is shown in Figure 3 as a function of the deceleration, as well as the maximum effective stress on the flexural tensile side. If the effective stress exceeds the yield stress of 616.5 MPa (at approx. 80 g), the material starts to flow. When the bolt has reached the yield stress across the whole cross section only little additional load can be borne before the bolt fails completely. With the assumptions made for the investigation performed this critical load is above approx. 145 g.

Taking the deformation results of the FE simulation the distance of the surfaces of the primary lid and the cask body at the position, where in reality the metallic seal is mounted, was determined. With this, the corresponding spring force of the seal or the gap between seal and sealing surface was deduced by using the load–deflection function of the seal (spring characteristic).

INVESTIGATION OF THE BEHAVIOUR OF SECONDARY LID AND SHOCK ABSORBER

During the assumed accident the cask drops with the face of the lid-end shock absorber onto the ground. Being much more flexible than the rather stiff rim of the cask, the secondary lid is bent into the cavity between the two lids while the container punches into the shock absorber circularly. Due to the deflection of the secondary lid a contact of the two lids may occur. This would lead to a decrease of the force the primary lid bolts are subjected to and thus, regarding their failure, lead to an increase of the tolerable impact decelerations. For the investigation of this sub-problem another FE model was implemented, which contained the secondary lid, the rim of the cask body and the shock absorber with an integrated protection plate (Figure 4). The secondary lid and the side wall of the cask are represented by a circular plate. The nodes in the marginal area of this plate are prevented from radial and tangential movement by boundary conditions to simulate the

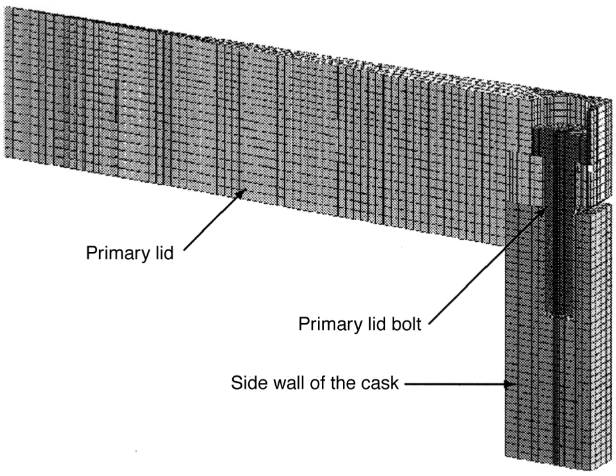

Figure 2. Cross section of the FE model for the primary lid examination.

rigid container wall. Also the nodes on the symmetry planes are restricted from tangential displacement.

The cylinder representing the shock absorber is taken to be a homogeneous material, which implements the compound behaviour of the sheet metal structure of the shock absorber lining as well as the energy absorbing wood material. The inelastic deformation behaviour of this material was implemented with ABAQUS' material model 'CRUSHABLE FOAM'. For this purpose dynamic impact tests with cylindrical partly encapsulated spruce-wood specimens[7] were recalculated to determine appropriate parameter values, which result in a satisfying agreement with the test data. The parts of the container not explicitly implemented in the model are considered by mass elements. Except for the rigid underground, which consists of special rigid elements, all components are elemented with isoparametric, three-dimensional, cubic continuum elements with linear interpolation and reduced integration.

With this model dynamic simulations were performed where the modelled components impact on the rigid target with an initial velocity. From the calculated data the deformation behaviour of the secondary lid was determined as well as its stressing.

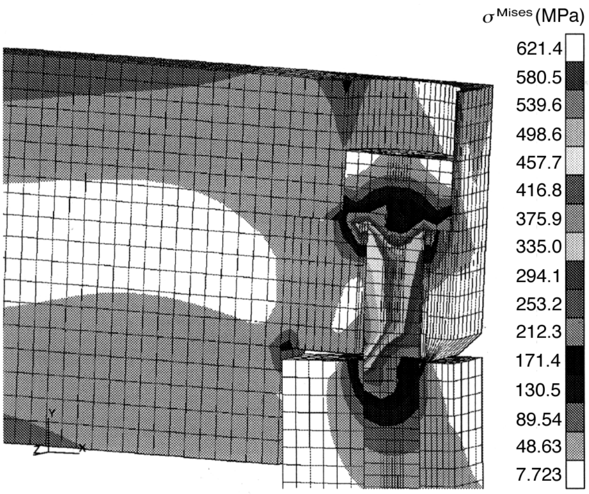

Figure 3. Deformation and stress distribution in the model for an impact deceleration of 77 g.

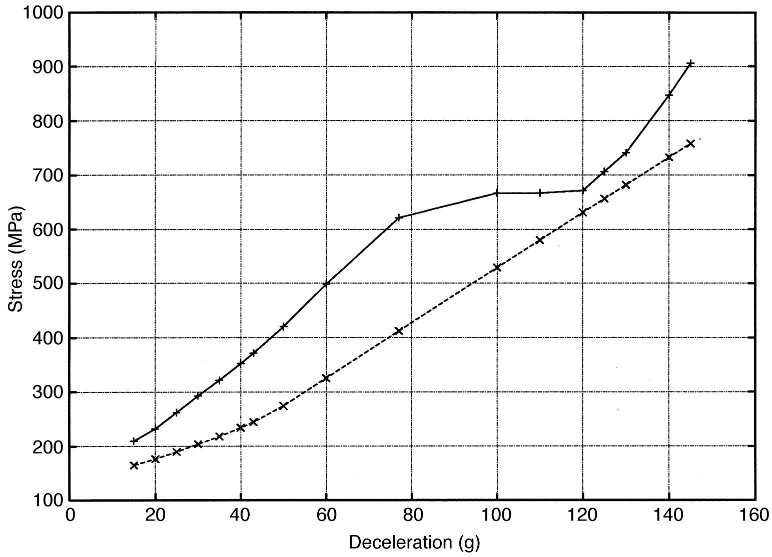

Figure 4. Maximum effective stress on the flexural tensile side (–+–) and nominal average axial stress (F_s/A_o (– –×– –) (A_0 initial cross sectional area) of the primary lid bolts as function of the impact deceleration.

From correlation of the results of the primary and secondary lid analysis the maximum impact deceleration occurring at the end of the impact is evaluated. To check whether both lids come in contact the deformation results of the primary lid calculation for this deceleration value are used.

Using these results it was verified that in the range of impact decelerations studied (up to the failure of the primary lid bolts) the two lids do not come into contact. However, an underestimation of possible supporting effects results from neglect of the polyethylene moderator plate in the cavity. This represents a conservative approach with regard to the bolt load.

DROP ONTO YIELDING TARGETS

In order to describe the interaction of the impacting container with a yielding target an analytical method is used. The shock absorber of the cask and the assumed real target are represented by two series-connected springs. The non-linear spring characteristic of the shock absorber is determined using data from dynamic crush tests with partly encapsulated spruce-wood specimens. The non-linear spring characteristic of the real targets is calculated from their material data presuming a specific failure behaviour. The exact methodology for the calculation of the maximum impact deceleration for impacts onto different real targets and impact velocities is described elsewhere[1,2]. A representation of this relation is shown in Figure 5 for three different types of ground (compacted sand, marly soil and rock). Using this method it is possible to correlate the behaviour of the lid system and its sealing function for the assumed accident scenario with the impact velocity onto different real targets.

The dependence between impact velocity onto these real targets and the gap width between seal and sealing surface or the spring force of the seal are listed in Table 1. Besides rock, for which a linear spring characteristic without failure was considered, the target deformation during the impact was calculated by using a foundation failure model. In order to consider impact conditions, the static values of the loads which lead to the foundation failure were multiplied by dynamic factors of 2.0 for cohesive soil (marly soil) and 1.5 for non-cohesive soil (sand). The assumption for the rock's behaviour, of course, is very conservative concerning the impact decelerations, since a failure of the rock under such high loads seems likely to occur in reality. This would lead to lower impact decelerations.

SUMMARY AND CONCLUSIONS

In the framework of this study the behaviour of a representative cask design in a rail transport accident was investigated. In doing this a reference cask was subjected to loads exceeding the loads observed during the drop from 9 m height onto an unyielding target. As a scenario the head-on impact onto the lid-side shock absorber was chosen. With respect to the release of radioactive substances the sealing function of the inner lid of the double lid system was examined.

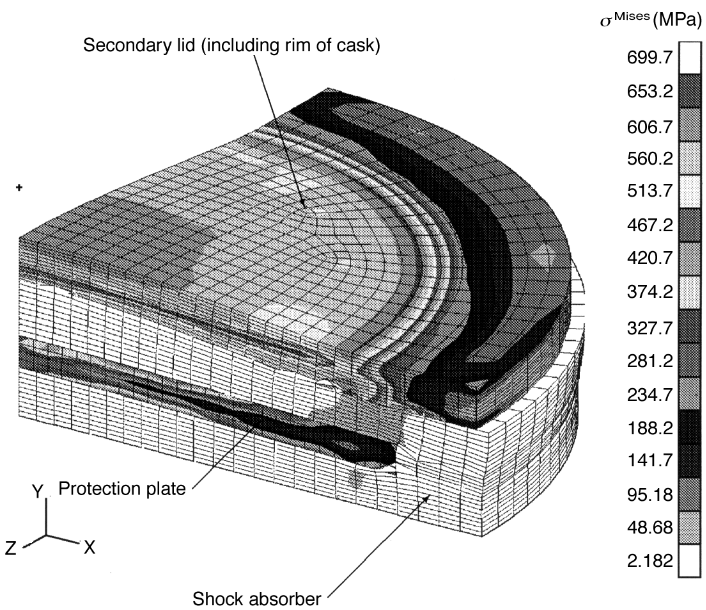

Figure 5. FE model used for the examination of the secondary lid. Deformations and stress distribution for an impact velocity of 18.5 m.s^{-1}.

Table 1. Behaviour of the primary lid screw joint as function of the impact velocity onto targets of marly soil, compacted sand rock and an unyielding target. For calculation of the gap between seal and sealing surface a springing back of the seal of 0.4 mm was assumed. For the rock target no failure of the rock by spalling or breaking is taken into account.

Impact velocity m/s					At maximum load		After impact		
IAEA	Rock	Compacted sand	Marly soil	Maximum deceleration (g)	Contact line force at seal ($N.mm^{-1}$)	Gap at seal (mm)	Contact line force at ($N.mm^{-1}$)	Gap at seal seal(mm)	Leakage rate $mbar.l.s^{-1}$
1.33	1.44	2.28	2.4	15	313.37	0	373.01	0	10^{-7}
1.77	1.92	3.04	3.2	20	283.55	0	373.01	0	10^{-7}
2.17	2.4	3.79	4	25	238.82	0	373.01	0	10^{-7}
2.62	2.88	4.55	4.8	30	194.1	0	373.01	0	10^{-7}
4.38	4.61	6.18	6.42	35	164.28	0	373.01	0	10^{-7}
6.72	6.91	8.36	8.6	40	119.55	0	373.01	0	10^{-7}
7.9	8.08	9.53	9.77	43	104.64	0	373.01	0	10^{-7}
10.36	10.55	12.08	12.34	50	45	0	373.01	0	10^{-7}
11.87	12.11	14.02	14.83	60	30	0	reduced	0	10^{-7}
13.38	13.73	18.42	21.77	77	7.5	0	reduced	0	10^{-7}
14.35	14.9	27.96	34.48	100	0	0.12	reduced	0	$\leq 10^{-5}$
14.79	15.44	33.29	41.48	110	0	0.2	reduced	0	$\leq 10^{-5}$
15.26	16	39.33	49.37	120	0	1	0	0.05	gap width dependent
15.5	16.3	42.61	53.64	125	0	2.56	0	1.45	gap width dependent
15.75	16.6	46.07	55.76	130	0	4.22	0	3.06	gap width dependent
16.27	17.22	53.5	56.34	140	0	8.12	0	6.85	gap width dependent
16.54	17.54	57.48	56.65	145	0	10.34	0	9.01	gap width dependent

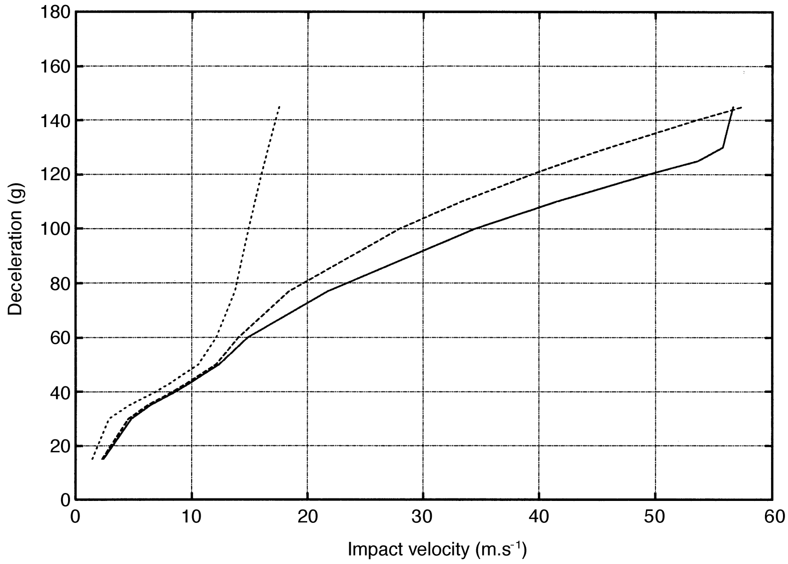

Figure 6. Relation between the maximum impact deceleration and the impact velocities onto targets of marly soil (—), compacted sand (– – – –) and rock (. . .). Besides rock, for which a linear spring behaviour without failure was considered, the target deformation during the impact was calculated by using a foundation failure model.

The maximum load the primary lid bolts are able to withstand before the hypothetical failure occurs was determined in a static calculation to be 145 g. This is approximately two times the value obtained for the 9 m drop onto the unyielding target.

Using an analytical method, suitable for the estimation of loads on casks impacting real targets, the results obtained from the FE calculations were correlated with impact velocities onto real targets. With the assumptions made this leads to maximum impact velocities of around 55 $m.s^{-1}$ for marly soil and sand and approx. 17 $m.s^{-1}$ for rock by taking only its elastic reaction and no failure into account. These figures are not meant to be exact limits above which the cask will fail inevitably. It has to be kept in mind that they only represent the results found on the basis of the conservative assumptions that were made using the methodology described.

While for the two 'soft' targets (sand, marly soil) which are implemented with a deformational behaviour taking their failure during the impact into account, quite high impact velocities are permissible, the rather low impact velocity calculated for the impact onto rock indicates that there is a need for further investigations to obtain more exact predictions of the safety margins in these cases.

In further studies a broader range of target types, especially stratified foundations, should be taken into account and also the following assumptions should be reconsidered to reduce the underestimation of the safety margins.

(1) The static inertia force of the lid and contents used in the study performed as load on the primary lid bolts, with respect to the highly dynamic interaction of the various more or less uncoupled masses (e.g. lid, fuel elements, fuel element basket) during the impact, is a rather conservative assumption. Implementing the process in a more realistic way might lead to a significant reduction of the load of the primary lid bolts.

(2) Considering the effect of the moderating plate in the cavity between the primary and the secondary lid would lead to a reduction of the deflection of the primary lid during the impact and so would also result in a reduction of the bolts' load.

(3) A more realistic implementation of the behaviour of hard targets (rock) with consideration of spalling, fracture and following displacement of these fragments could result in higher permissible impact velocities for impacts onto these targets.

(4) The head-on impact is by far the most damaging orientation with respect to the loading of the bolts. Considering even small deviations from the exact plain impact leads to a significantly lower loading of the bolts. Therefore the correlation of the findings with probabilistic data about cask orientation and also target types and impact velocities is necessary to permit a more general prediction.

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