STRAIN OF LID BOLTS OF TYPE B PACKAGES DURING 9 M DROP TESTS – RESULTS OF REAL TESTS AND PROBLEMS OF ANALYTICAL PREDICTION

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ABSTRACT

MOSAIK II-15 casks were designed for the transport of different types of radioactive waste, among others heavy scrap compacts and steel drums with conditioned radioactive material. According to the results of analytical predictions the mass of contents must be limited to specified values in order to avoid inadmissible strains of cask lid and lid bolts under IAEA test conditions, especially during drops flat onto the lid side impact limiter. Among others, high stresses were expected which are caused by interactions between free movable solid contents and the cask lid during the final phase of impact or the rebound of the package. Therefore, additional tests which have been performed with the package had two objectives: General check of the results of mechanical analyses, and, moreover, quantification of effects resulting from interactions between the package components that can be increased because of gaps between the containment components, the inner lead shielding and contents. The paper presents results of calculations and tests performed for two different package modifications: (1) cask with inner lead shielding loaded with close packed steel bars; small gaps between the package components, (2) cask without inner lead shielding loaded with a steel drum that was filled with steel scrap in a concrete matrix; large axial gap between the drum and cask lid.

INTRODUCTION

The requirements for casks used for transport of radioactive material are defined in the IAEA Regulations T-SR-1 [1]. The regulations allow safety proofs by tests with prototype and model casks as well as by mechanical analyses. It is one of usual practices to perform mechanical accident analyses for package components with consideration of the maximum acceleration that packages subject during the impacts onto the target. This can be a conservative approach but its conservatism is not generally evident. Results of FEM analyses do often not have the necessary level of confidence because of problems with modelling of the material characteristics (e.g., the character-istics of wooden impact limiters). Therefore, sometimes are real tests the only possibility to get sufficient evidence about the behaviour of cask components during accidents and the resulting stresses and strains. This illustrates the example discussed in this paper.

Primary reason for the tests reported about was the limitation of contents masses included in the approval certificates for MOSAIK II-15 casks. The discussion of the test program prepared by the firm GNS with BAM led to an expansion of the original program. Particularly, BAM required to include the experimental investigation of effects of interactions between the package components (cask, inner shielding, contents) that can appear if radial and axial gaps exist between [2]. The tests were carried out by GNS. All tests were accompanyed by BAM representatives.

TEST OBJECT: THE MOSAIK II-15 CASK

MOSAIK II-15 casks manufactured in several modifications are used for transport of different types of radioactive waste with heat generations up to about 300 W. The most important design parameters of MOSAIK II-15 packages are summarized in Table 1.

With regard to the problems considered in this paper, contents were of primary interest that can cause large strains of the cask components during tests which are required in order to simulate accident scenarios. These are especially rigid contents without significant shock absorbing properties, e.g., metal scrap compacts, drums filled with conditioned waste, etc.

Table 1: Characteristics of MOSAIK II-15 packages

Cask	Lid	lid bolts	Contents	Shock absorber
- height: 1500 mm **- outer diameter:** 1060 mm **- wall thickness:** 160 mm **- material:** DCI **- inner shielding thickness (Pb):** 0 ... 140 mm	**- thickness/ thickness of flange:** 180/100 mm **- diameter/ outer diameter of flange :** 730/1060 mm **- material:** DCI	**- type:** 24 cylindrical head screws M36 **- material:** 8.8 (ferritic, $Rp_{0.2}$: 640 MPa) or A2-70 (austenitic $Rp_{0.2}$: 250 MPa)	Different waste, e.g., dried concentrates dewatered ion exchange resins, activated core internals, metallic objects and solids ...	**- effective thickness)*:** 200 mm **- material:** pine-tree)* lid side shock absorber

OBJECTIVE OF THE TESTS

Original objective of the tests (realized in test no. 1) was the experimental check of the results of analytical calculations. Background was a guessed overestimation of the strains in the cask lid and the lid bolts under IAEA test conditions, especially during a 9 m vertical drop onto the lid side impact limiter. Due to the results of the calculations for that case the contents masses specified in the approval certificates for the MOSAIK packages were limited: E.g., by MOSAIK II-15 contents masses are allowed to transport between 810 kg (no shielding, A2-70), 430 kg (80 mm, A2-70) and 230 kg (140 mm, 8.8) depending on the thickness of the lead shielding and used screw material (in brackets). It was assumed in these calculations that no significant interactions appear between contents, shielding and cask lid. This seemed to be a realistic approach for bulk contents (contents A, maximum filling).

With regard to unavoidable radial gaps between cask wall and shielding and axial gaps between contents and cask lid, it was intended in test no. 1 to take into consideration the most disadvantageous conditions. Of course, the gaps in test no. 1 mentioned in Table 2 would only exist if the tolerances of the cask component dimensions would combined as “worst case”. This was a requirement of BAM (as the competent authority for safety assessment and quality assurance of Type B packages in Germany) in order to cover the most unfavourable conditions in regard to the mobility of contents and shielding as well. Fig. 1 (left) shows the axial cross section of the test package before dropping.

Objective of test no. 2 was the investigation of effects resulting from interactions between non-fixed rigid contents and the cask lid if there exist large gaps between. Contents of that type (contents B) are, e.g., drums filled with concrete-conditioned waste or metal scrap compacts. Significant interactions one have to expect, e.g., at 9 m drops onto the lid side impact limiter. Stress peaks in the lid and lid bolts were guessed especially if the contents would strike on the package lid after the impact of the cask on the target or its rebound. On principle, such conditions would require the consideration of a package as a system consisting of two (or more) single masses.

Test no. 2 simulates the conditions expected if casks are loaded with a steel drum filled with waste in a concrete matrix. The desired conditions are provoked by the large axial gap (255 mm) between drum and cask bottom (Fig. 1, right). It was expected that a contents-lid interaction could happen some milli-seconds (theoretically up to more than 15 ms) after the cask impact onto the target. In order to have unambiguous conditions during the test the axial movement of the drum in the cask was guided by guiding rails. Important conditions and parameters of the test are summarized in Table 2.

Table 2: Test conditions

Parameter	Test 1	Test 2
drop height	9 m	9 m
temperature	not specified (ambient temperature)	not specified (ambient temperature)
Test position	vertical; lid-side impact limiter	vertical; lid-side impact limiter
contents	- **mass:** 770 kg - **specification:** thin steel bars, 860 mm long (simulating, e.g., absorber rods)	- **mass:** 1250 kg - **specification:** steel drum, ∅ max. 625*885 mm filled with steel scrap, cast with cement
package specifications	- thickness of lead shielding: 120 mm - lid bolt material: 8.8 (ferritic steel)	- thickness of lead shielding: no lead shielding - lid bolt material: 8.8 (ferritic steel)
special conditions (at test position before drop)	- **contents:** 30 mm free axial gap - **shielding:** axial (about 4 mm) and radial gaps (about 7 mm) between shielding and cask lid/cask wall	- 255 mm axial gap between drum and bottom of cask - drum not locked but axially guided

RESULTS OF MECHANICAL ANALYSES

The limits of contents masses for type A contents mentioned above were calculated with consideration of stress limitations to 67 % and 50 % of the 0.2% yield stress for the bolts and the DCI lid, respectively. The calculations were based upon a rather simple model. Interactions between lead shielding and cask lid were not taken into consideration assuming that there no axial gap exists between shielding and cask lid and that the influence of the small gap between contents and lid can be neglected. More exact FEM calculations were performed by GNS/GNB for a package with a lead shielding thickness of 120 mm and a contents mass of 326 kg (MOSAIK II-15 P/U), i.e, with the exception of contents mass for the same conditions as in test no. 2. According to these calculations the stresses amount to 40 MPa in the lid and 244 MPa (equivalent stress) in the ferritic (8.8) lid bolts.

BAM performed calculations for contents B (test no. 2) after the test. Primary objective was the validation of options used for modelling of the geometrical and material characteristics of cask components. The ABAQUS FE program [3] was used to simulate the drop conditions. An elastic-plastic material law with a 'von Mises' yield condition was assumed for the metallic components of the cask. The shock absorber was modelled as a homogeneous material that considers the compound behavior of the sheet structure as well as the energy absorbing characteristics of the wood enclosed therein [4]. The ABAQUS 'crushable foam' model was used to model the inelastic behavior of the shock absorber. Exept of the bolts wich consists of spring elements all components are elemented with isoparametric three-dimensional cubic continuum elements with linear interpolation and reduced integration.

Concerning the deflection of cask lid (Fig. 2), the results of calculations show a good agreement with the test results (Fig. 3b). The calculated maximum stress in the centre of lid amounts to 145 MPa.

TEST RESULTS

The most important result of the tests was the experimental confirmation that the maximum strains of the cask components strongly depend on the geometrical and material characteristics of the contents and its possibility to interact with the cask components. Especially, contents B, i.e., rigid bodies that do not totally occupy the inner volume of the cask can lead to stress peaks that are much higher than those for bulk contents which fill the volume almost fully. This is the consequence of a more or less effective reaction between the contents and the cask (momentum due to disappearance of deformations) at the moment of the release of the package. Due to this effect, the downward motion of the contents starts later than that of the cask. Owing to this, the contents strikes the cask lid with a velocity of about 13 m/s when the cask velocity is already reduced to lower values. Because of the geometrical conditions, i.e., the gaps between contents, shielding, cask wall and cask lid, this effect has been expected in a mitigated form also during test no. 1. However, the analyses of all test results (especially the accelerations) did not give indication for it. Probably, the mobility of contents was restricted or impossible, e.g. due to friction forces which reduced the effectiveness of the momentum after the release of the package.

Figs. 3a and 3b demonstrates clearly the widely differing results of tests no. 1 and 2 illustrated by the the velocities of the center of the cask lid after the impact of the cask on the target. Fig. 3a shows these velocities (i.e., the integrated decelerations that are measured in the center of the lid) for the tests with the contents A and B. In comparison with the nearly smooth curve for contents A indicating no interactions between contents and cask lid the lid velocity began strongly to oscillate in test no. 2 after the contents struck the cask lid (ca.10 ms). The course of deflections of the lid center (Fig. 3b; 300 Hz high-pass filtered integral of lid velocities) demonstrates this effect likewise. The maximum deflection during test no. 2 lay about one order of magnitude beyond that evaluated for test no. 1.

The lid bolt strains measured during test no. 2 (contents B) are shown in Fig. 3c. The figure illustrates unambigously the coincidence of the maxima and mimima of the portions of the tension and bending components caused by the drop with the maxima and minima of the bending of the lid center (Fig. 3b). With consideration of the stresses due to the tightening torque (i.e., a membrane strain of about 930 µm/m) the maximum stresses in the bolts amount to values in the range of the 0.2 % yield stress of the bolt material (8.8; 640 MPa). It happened immediately after the contents struck the cask lid producing bending and tension strain components of about 1100 and 900 µm/m, respectively. The course of the bolt strains reflects also the second contact between drum and cask lid after the contents rebound phase (about 16 ms after the impact of the cask). It can be also recognized in Fig. 3b by the increased amplitude of the deflection and the short-time change of the frequency of the deflection oscillations.

In comparison with the bolt stresses during test no.2 the maximum stresses during test no.1 were rather low. Though the signals of strain gauges were strongly impaired by oscillations presumably caused by electric effects, it could be shown on the basis of low-pass filterings with different frequencies (3000 to 500 Hz) that the portion of the strains caused by the test did not overstep 400 µm/m. With consideration of the pretension the total stress reached a level that was not higher then about 280 MPa. This is a rather low value compared with the result of above mentioned calculations performed for the MOSAIK II-15 P/U package because of the different masses of contents that must taken into consideration (test no. 1: 770 kg, calculation 326 kg).

The effect of interactions between contents and cask lid during test no. 2 is illustrated in Fig. 4 more clearly by the integrals of the measured accelerations, i.e. the velocities of cask lid, cask bottom and contents (drum). The first interaction between drum and cask lid about 10 ms after the cask impact is reflected by the increase of the velocity of the lid centre and (with some delay) of the bottom as well as by a strong decrease of the velocity of the drum. Until that interaction the velocity of the drum remained nearly 13.3 m/s, i.e., it was not influenced by contacts with other package components.

SUMMARY AND CONCLUSIONS

9 m drop tests were performed with a MOSAIK cask in order to check the results of calculations with different approaches and to evaluate stress increasing effects that can possibly result from interactions between the cask components and the contents. The test results illustrate the problem of a realistic modelling of the package components with consideration of all effects that can influence the stresses in the cask lid and lid bolts. Caution is required with approches which are based on the calculation of the maximum deceleration of the package during the impact. A "black-box" cask model can lead to conservative results but to an underestimation of the stresses as well.

With regard to contents specified in this paper as contents A the original limitation of the contents mass for MOSAIK casks seems to be conservative approaches, but a verification is necessary for conditions different to those in test no. 1 (lead shielding thicknesses, content masses). The test results confirm that high stresses in containment components are avoidable if gaps in the package are as small as possible in order to minimize interactions due to different component velocities during the course of impact that result in significant momentum reactions.

The results of tests with simulation of the conditions in casks loaded with rigid non-locked contents show that the interactions between the cask components and its interactions with the contents can cause very high stresses in the cask lid and lid bolts. Especially, a failure or an inadmissible strain of the bolts cannot be excluded if rigid contents would strike the cask lid during the rebound of the cask after its impact. This conclusion is based on results of other tests with Type B packages performed by BAM in the past.

In order to avoid stress peaks in cask lids and lid bolts during accidents that are caused by contents specified in this paper as contents B, special solutions should be prepared precautionary as part of the cask design to mimimize the axial and/or radial gaps that would exist because of the geometry and the dimensions of contents. Preferably, the gaps should be closed by filling materials or structural components with shock limiting characteristics.

It is possible to estimate the effects caused by non-locked rigid contents during 9 m drop tests also by mechanical analyses. However, an important but difficult (i.e., non-trivial) part of such analyses is the calculation of the span between the impacts of cask and contents that has a substantial influence on the estimated stresses in the lid and lid bolts.

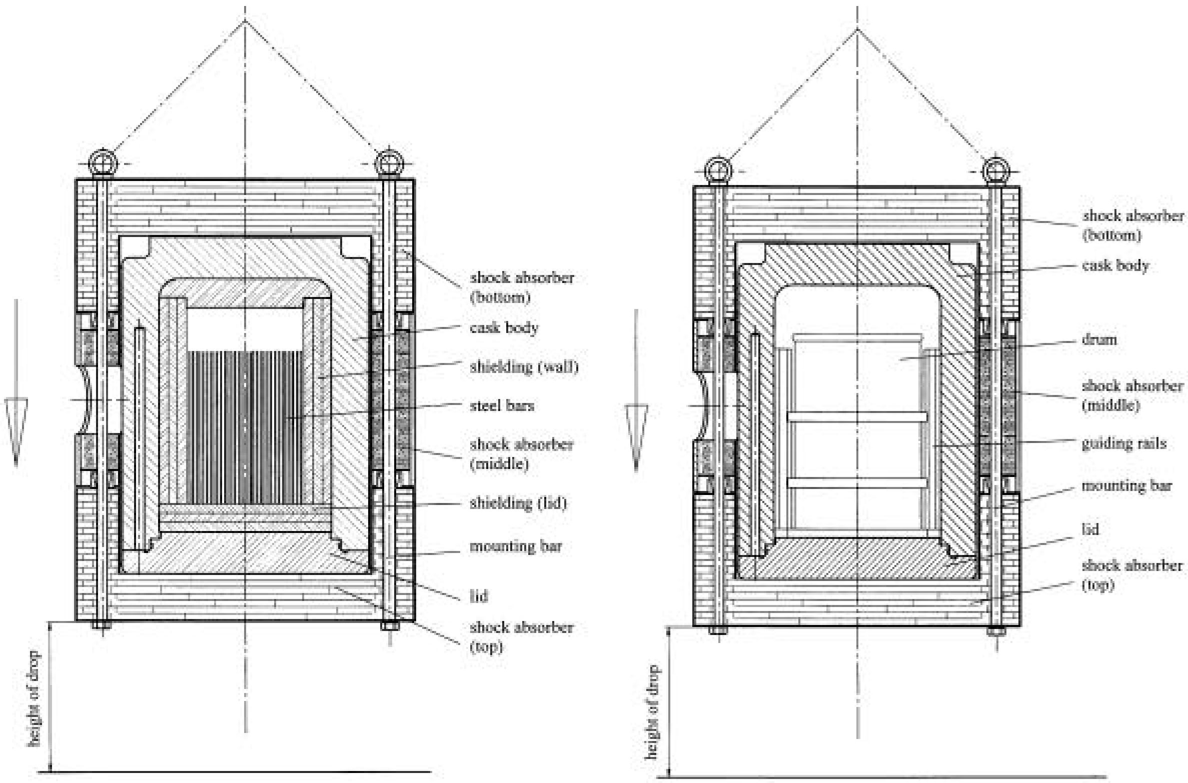

Fig. 1: MOSAIK packages loaded with contents A and B (left: test no. 1, right: test no. 2)

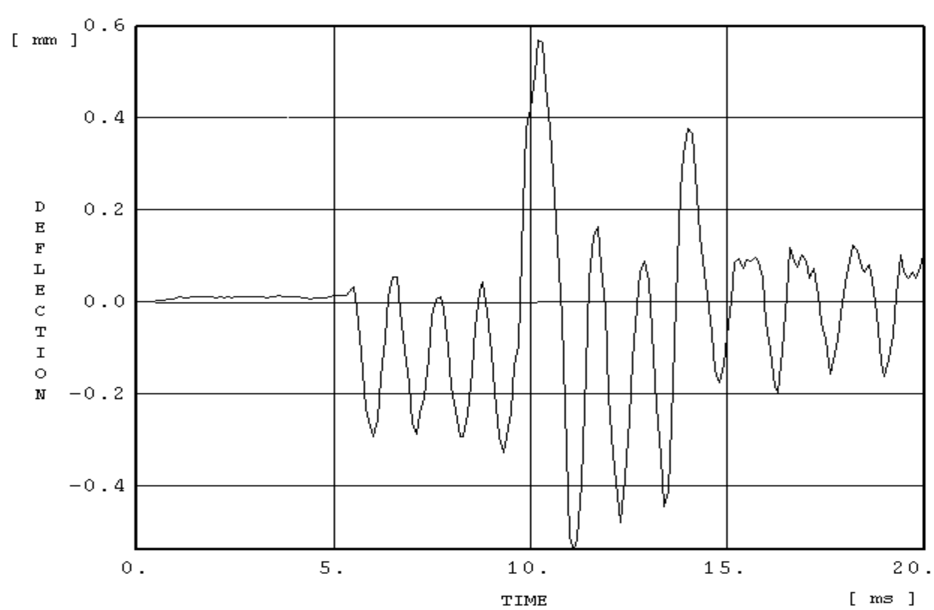

Fig. 2: Deflection of the lid of the cask centre during test no. 2 (finite element simulation)
Take notice that the positive sign in this figure means (contrary to Fig. 3b) a deflection in drop direction.

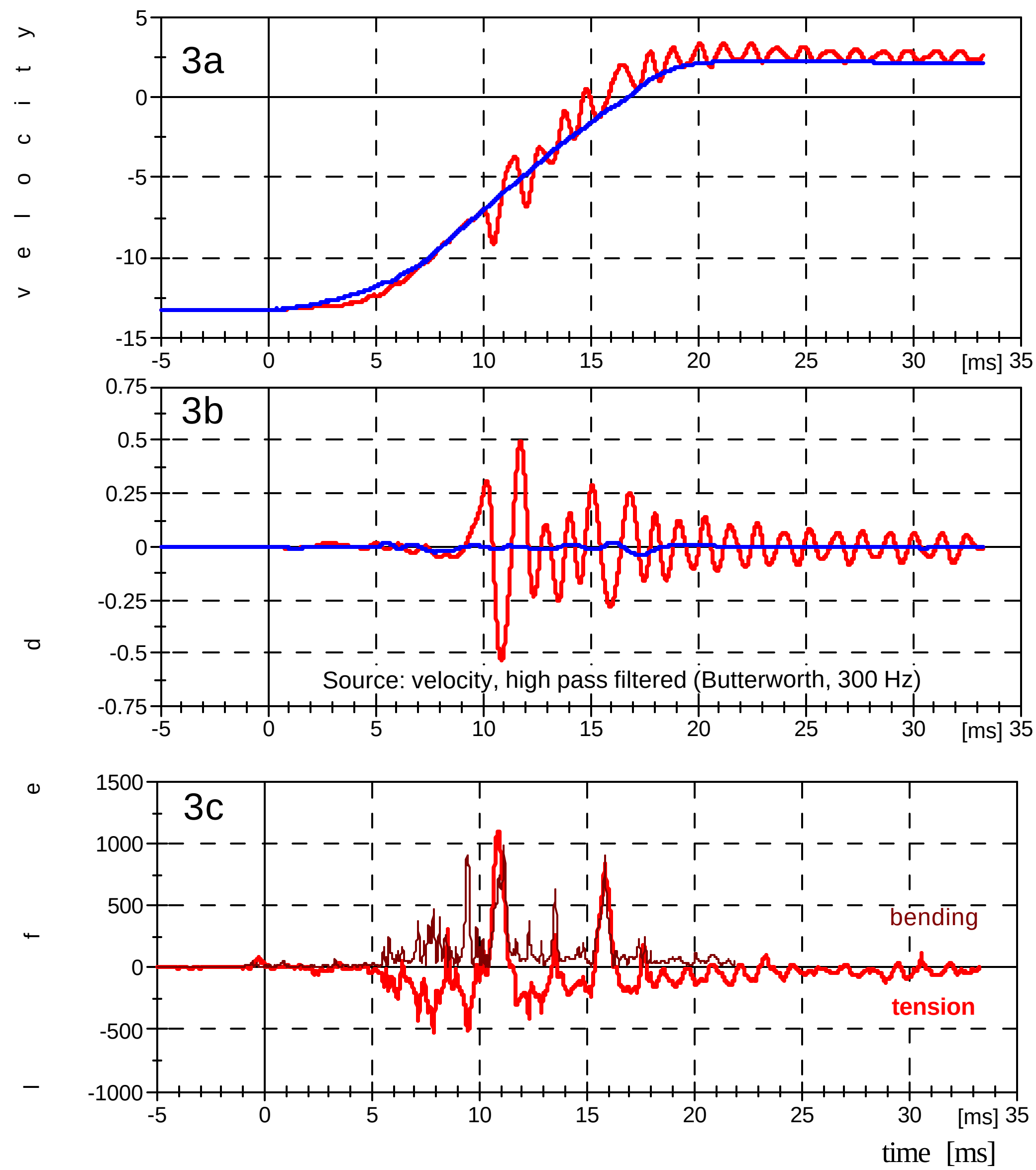

Fig. 3: Results of tests no. 1 (contents A, blue curves) and no. 2 (contents B, red curves)

3a: Velocity of lid centre

3b: Deflection of lid centre

3c: Lid bolt strains (only test no. 2)

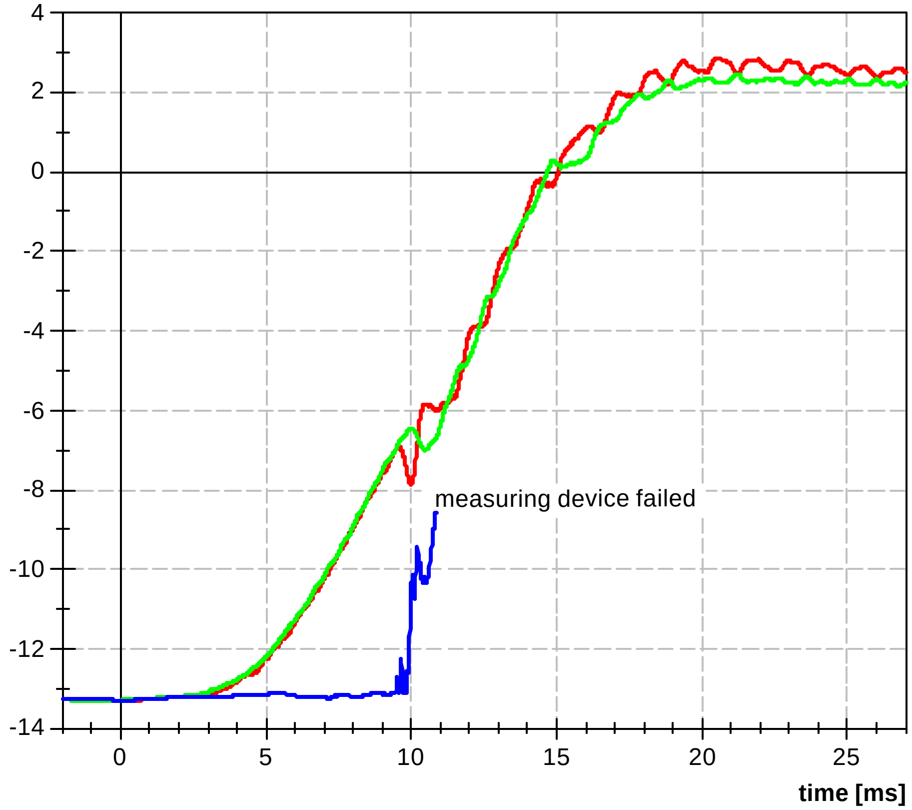

Fig. 4: Test no. 2 (contents B); velocities of cask lid (red), cask bottom (green) and drum (blue)

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