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CONSTOR® V/TC Drop Tests. Pre-Test Analysis by Finite Element Method

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1. Introduction

The CONSTOR® family of steel-concrete-steel sandwich cask designs have been developed to fulfil both the internationally valid IAEA criteria for transportation and the requirements for long-term intermediate storage in the US and various European countries. A comprehensive drop testing programme using a full-scale prototype test cask (CONSTOR® V/TC) has been developed as part of the application for a transport license in both Germany and the US. The drop tests using the full-scale cask will be performed by BAM at test facilities in Horstwalde. The tests will include five different 9m drops onto flat unyielding targets and seven different 1m drops onto a punch. The first drop test, a 9m side drop, will be performed during PATRAM 2004. The other drop tests will take place during the following year.

The development of the cask design and the formulation of the drop test programme has been supported by an extensive series of finite element analyses.

The objectives of the finite element analyses were;

- to provide an intermediate step in demonstrating the performance of the CONSTOR® in fulfilling the requirements of 10 CFR 71 and the IAEA transport regulations.
- to justify the selection of drop tests.
- to predict the performance of V/TC during the drop tests.
- to estimate the strain and acceleration time histories at measuring points on the test cask and to aid in the setting up of the test instrumentation.
- to develop an analysis model that can be used in future safety analyses for transport and storage license applications and which can confidently be used to demonstrate the performance of the package.

This paper presents an overview of the analyses performed, including a summary of all the different drop orientations that were considered. The major assumptions employed during the analyses are also discussed, as are the specifics of the modelling techniques that were employed. At the end of the paper, the key results obtained from the analyses are presented along with several conclusions relating to the objectives outlined above.

2. Modelling Overview and Discussion of Major Assumptions

The analyses performed included all of the drop tests outlined in the drop test programme [1]. The analyses also covered additional cases to demonstrate that the scenarios chosen for drop testing are the worst case. Other cases were also included to evaluate the sensitivity of results to uncertain parameters. The complete list of scenarios analysed are as follows:

Test Number	Description
A1	9m side drop
A1a	9m side drop onto a trunnion
C1	9m lid down drop
E1	9m base down drop
D1	9m base edge drop
C1a	9m lid edge drop
D1a	Tip-over after 9m base edge drop
B1b	Derivation of worst oblique angles
B1	9m oblique drop onto the lid
B1c	9m oblique drop onto the base
B1a	9m oblique drop onto the base, onto a trunnion at the lid end on second impact
A2	1m side punch drop onto the base impact limiter
B2	1m side punch drop onto the lid impact limiter
C2	1m lid down punch drop
D1b	1m base edge punch drop
E1a	1m base down punch drop
E2	1m side punch drop onto an undisturbed surface of the overpack
E3	1m side punch drop onto a joint between the two halves of the overpack
E4	1m side punch drop without the overpack
A1b	9m side drop with failed welds and uncontained wood in impact limiters
A1c	9m side drop with low tensile strength concrete
C1b	9m lid down drop with full thickness perforated partitioning plate on symmetry plane

The analyses were carried out in parallel with the manufacturing programme for the full-scale test cask. At the same time a programme of concrete testing was being undertaken to further verify the material properties of the concrete used in the manufacturing. Hence at the time when the model was being built neither the as-built material properties, nor the as-built geometrical details of the test cask were available. This obviously affects the comparison of the analysis results against the drop test performance of the test cask. The analytical modelling of the test cask was based upon the relevant design drawings and design material specifications. Since one of the primary objectives of the analyses was to provide an intermediate step to demonstrate the performance of the package, analyses assumptions, material properties and analyses methods were chosen so that results from the analyses - in terms of stresses and strains in the containment of the package – would be conservative. Approximation to behaviour during the drop test was a secondary consideration.

As one test cask will be used for the whole series of drop tests, any permanent damage to the cask will be cumulative. It is impractical however to analyse the drops strictly in the sequence of the drop tests and to accumulate the damage in a model through a sequence of analyses. Instead, each drop scenario was analysed with a pristine undamaged model. For the 9m drops, as permanent deformations in the cask itself are expected to be local and minor, assuming a pristine cask at the beginning of each drop analysis is not unreasonable. Although the concrete will crack further in each drop and damage will be cumulative, the extent of cracking in the concrete at the start of a drop is unlikely to have a major significant effect on the results because the steel liners carry the majority of the applied loads. For the 1m drops, as the permanent deformations are likely to be local, and are not likely to extend to the punch impact location in the next drop, this assumption is also satisfactory.

In reality for drop tests A2, B2, C2, D2 and E1a, the punch will impact an impact limiter which has already been damaged in a preceding 9m drop. The details of how the impact limiters will deform during the 9m drops can only be estimated. Predicting how a damaged impact limiter will behave when impacted by a punch is also difficult. For this reason, the analyses relating to drops onto a punch were carried out with the pessimistic assumption that the punch impacts the pressure plate or protection ring of the impact limiter directly. In other words, it is assumed that the steel housing and the crushed wood of the impact limiters offer no protection during impact. This is a conservative assumption when considering the prediction of stress levels in the cask.

For drop cases where multiple impacts occur, for example, tip-over after the base edge drop (D1a) or any of the oblique drops, analysis was performed on two separate events, rather than modelling the whole multiple impact event as one. In these cases the first impact events were bounded by other drop orientations, and only the secondary impact was considered in detail, for example the slapdown onto the base impact limiter following an oblique drop onto the lid impact limiter (B1).

3. Modelling Methodology and Analysis Specifics

Each scenario was analysed using the explicit transient FE code LS-DYNA [2]. The analysis models represented the complete CONSTOR® V/TC package, including the impact limiters, the cask, the dummy basket and the overpack. All of these items were explicitly modelled in three dimensions. This methodology of considering the whole package provides a most realistic simulation of the package behaviour taking into account the complexity which arises from the three dimensional, transient and non-linear nature of the events and the interaction between the many components.

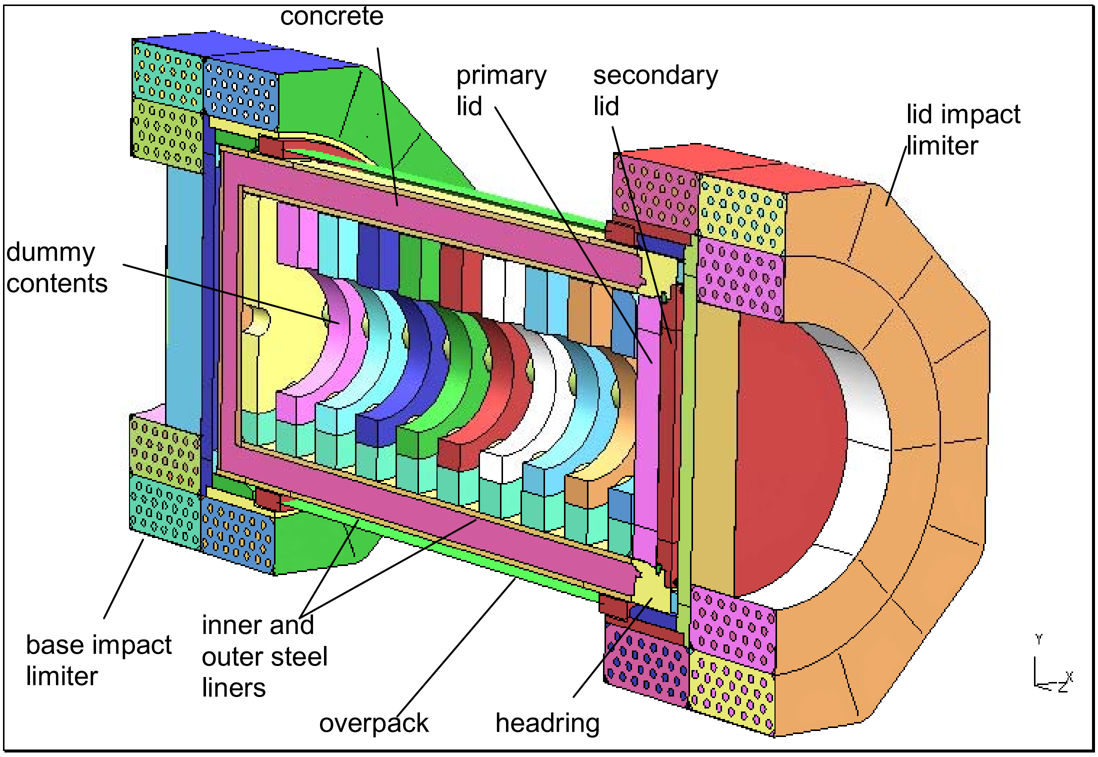

Fig. 1. Overall view of the finite element model used in the majority of the analyses, half model.

Taking advantage of symmetry of the package in the drop scenarios, half models (representing a 180° segment of the package) were used in all the analyses, except for the lid down and base down drops in which 1/8th models representing a 45° segment of the package were used. The half models consist of 1023917 nodes, 768068 solid elements, 855 beam elements, 129236 shell elements, and 482 spring elements.

The approach used in the modelling of individual components within the package was dependant upon the role they play in the overall performance of the V/TC during the drop tests. With a model of such complexity it is important to achieve an efficient overall mesh design so that analysis time and computing costs can be minimised. Where possible savings were made in the number of elements employed to represent a component. This was achieved for example by using shell elements to represent the overpack during the 9m drop analyses. However where individual components play a significant role in the overall package performance they were modelled in detail. The following paragraphs describe some of the details associated with the modelling of individual components of the package, and the LS-DYNA [2] options used.

The headring connects the inner and outer steel liners together at the top of the cask. It also provides surfaces for seating of the double lid system. In effect it is the interface between the lids and the rest of the cask body. The mesh in the headring around the lid to body interface was determined firstly by the mesh of the secondary lid bolts, and secondly by the radial location of the secondary lid metal O-ring seals. The number of elements between adjacent bolts was chosen to adequately simulate the stress variation around each bolt and between the bolts. The finite element mesh through a vertical section of the headring was designed so that the finest mesh was employed at the interfaces with the lids and where geometrical details are small. In these areas stress gradients are steep and the correct modelling of behaviour can only be achieved by employing a refined mesh. A finer mesh was also employed around the connections with the liners. The coarsest mesh was located towards the middle of the headring where stress gradients are expected to be smallest.

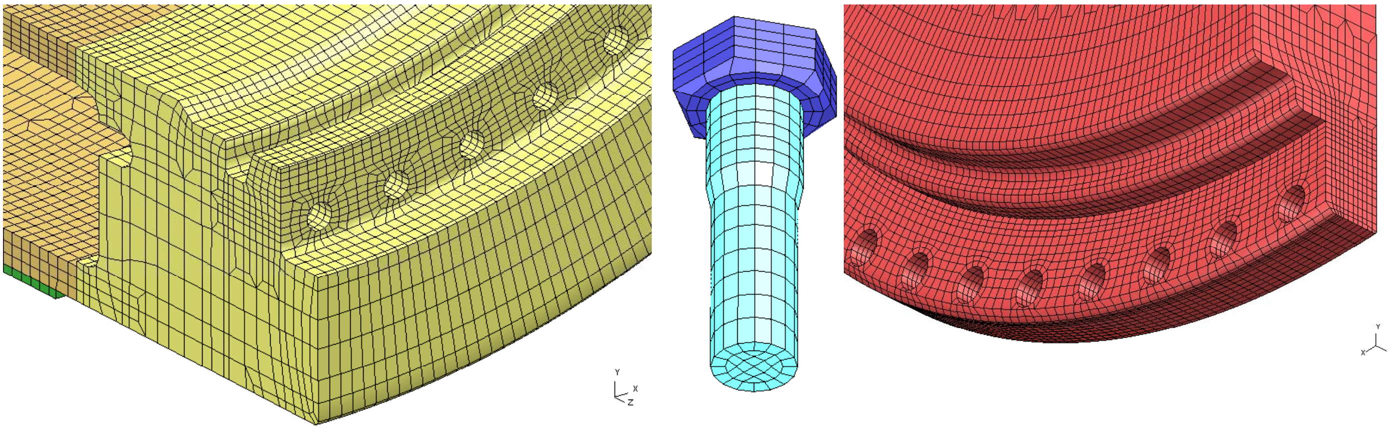

Fig. 2. Mesh details around the headring, bolts and secondary lid.

Each lid bolt was modelled in its entirety using solid elements, including the head, the shank and the threaded portion of the shank. The cross sectional area of the bolt mesh was adjusted to achieve the required tensile stress area. Bolt pre-loads were modelled in all of the analyses.

The reaction force from the compressed metal O-ring seals between the secondary lid and the headring is significant in comparison with the bolt pre-loads. These loads play a significant role in the dynamics of the lid and lid-body interface. Each seal was therefore modelled by a series of equispaced springs along the mid-diameter of the seal groove housing. The inner and outer steel liners, which form part of the sandwich wall design, were modelled using solid elements. For the most part they were modelled with three elements through the thickness except for most of the inner liner where five elements through the wall thickness were used. It was important to have as many elements through the thickness in the inner liner as possible because the inner liner forms part of the containment of the cask and the stresses need to be assessed against the rules of ASME [3] by “linearisation” into membrane, bending and shear stresses and as it is part of the containment, the stresses need to be assessed as accurately as is possible.

Between the inner and outer steel liners there is a layer of concrete. Inside the concrete a series of copper tube profiles aid in the dissipation of heat from the inside of the cask to its outer surface. The copper tubes are embedded within the concrete, and in turn, they segregate the concrete into discrete compartments. Instead of modelling each “compartment” of concrete as found within each tube and between the tubes separately, the whole cavity between the liners was modelled as a continuous whole. In a number of drop scenarios, the deflections in the cask wall will be sufficient to cause the concrete to crack. MAT_WINFRITH_CONCRETE was chosen as one of very few LS-DYNA material models that is capable of modelling both the compression and the tensile behaviour robustly.

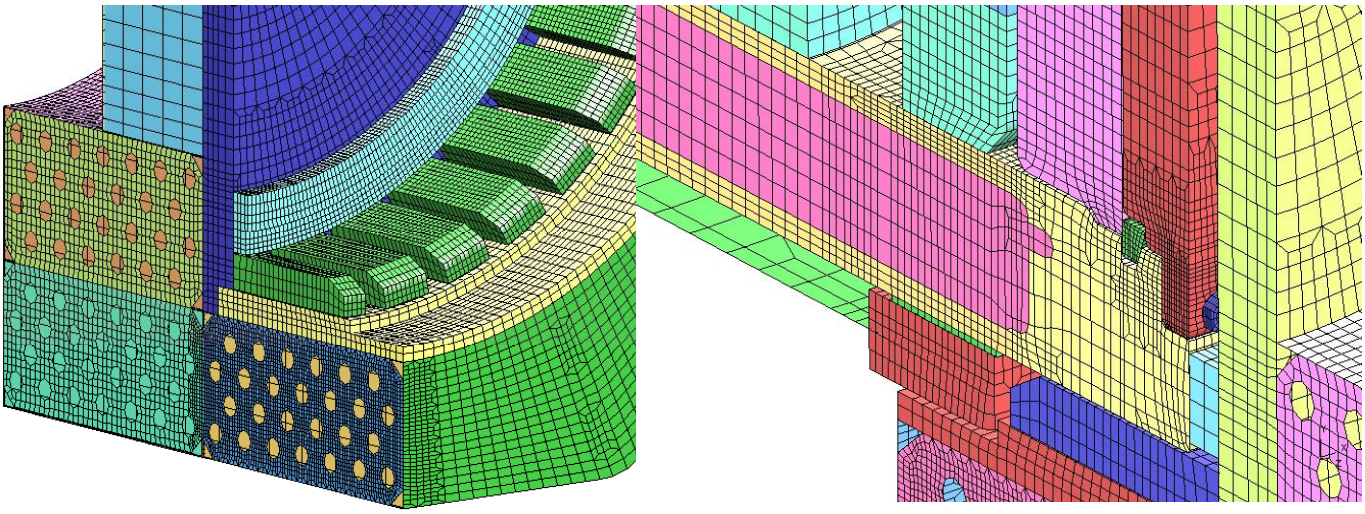

Fig. 3. Mesh details for impact limiter, and entire model shown at interface between cask (lid-side) and impact limiter

The impact limiters consist of wood blocks contained in compartments between relatively thin steel partitioning plates. The impact limiters also house pressure plates and protection rings which shield the lid systems and welded connections at the top and bottom of the cask from impact during a 1m drops onto a punch. The housing and the wood were modelled separately, with interaction between them modelled using contact surfaces. The housing was modelled using a mixture of shells and solids, and the wood was modelled using solids. The pressure plate, protection ring, the spacing ring and the spacing bars were modelled using solids. The rest of the structure consists of thin plates and was modelled using thin shell elements, located at the mid thickness of the plates, and assigned thickness as defined in the part list for the component. The pressure ring and the spacer bars are the only components of the impact limiter that will come into direct contact with the cask. They were therefore modelled with similar mesh refinement as the area of the cask they will contact.

In the transport configuration the package includes an overpack, which protects the steel liners and concrete from damage during a drop onto a punch. The overpack is essentially a thick steel cylinder formed from two halves which are bolted together to form a cladding around the outer liner. The overpack was modelled with solids at the top and the base ends where it interfaces with the impact limiters. Solid elements were also used along the connection joint between the two halves of the overpack. Elsewhere shell elements were used to represent the overpack during the 9m drop cases. For the punch drop events, where the overpack is impacted by the punch, solid elements were used in the vicinity of the impact. The solids at the top and base end of the overpack allow correct simulation of the significant load transfer between the impact limiter and the cask wall. The shells used to model the overpack away from these areas of high stresses allow correct simulation of the overall bending, axial and ovalisation behaviour.

The prototype test cask includes a dummy contents model which is designed to replicate the characteristics of the contents in a production cask. The dummy contents model consists of a series of large disks connected by several large steel pipes. The discs of the dummy basket were modelled with solids and the connecting pipes were modelled with shells. The areas of the discs that will contact the cavity in a drop scenario were modelled as deformable with the appropriate properties, whilst the areas that will not contact the cavity were modelled as rigid to economise on analysis time. This is justifiable as the discs are very stiff structures even in an ovalisation deflection, and modelling the overall stiffness as rigid is reasonable.

The majority of the analyses were performed using a two stage approach. In the first part of the analysis, ‘dynamic relaxation’, all of the applied bolt pre-loads and spring loadings were left to achieve an equilibrium state. The second part of the analysis, was concerned with the actual dynamic event in question. In the second stage of the analyses, initial velocities were prescribed to the model to represent the drop case in question. The package impacts upon a rigid planar target for the 9m drop cases and a representation of the punch for the punch drop tests. The analyses were left to run until all of the kinetic energy associated with the drop event had been converted into internal energy within the model.

4. Summary of Results

The behaviour of the package predicted to occur during the 9m side drop is illustrated in the figures below. Results can be interrogated at various discrete time points during the dynamic event   These snapshots were all taken at t= 0.018799s, at which the stresses were closest to the maximum. This was also the time at which stress in the containment were evaluated to ASME requirements.

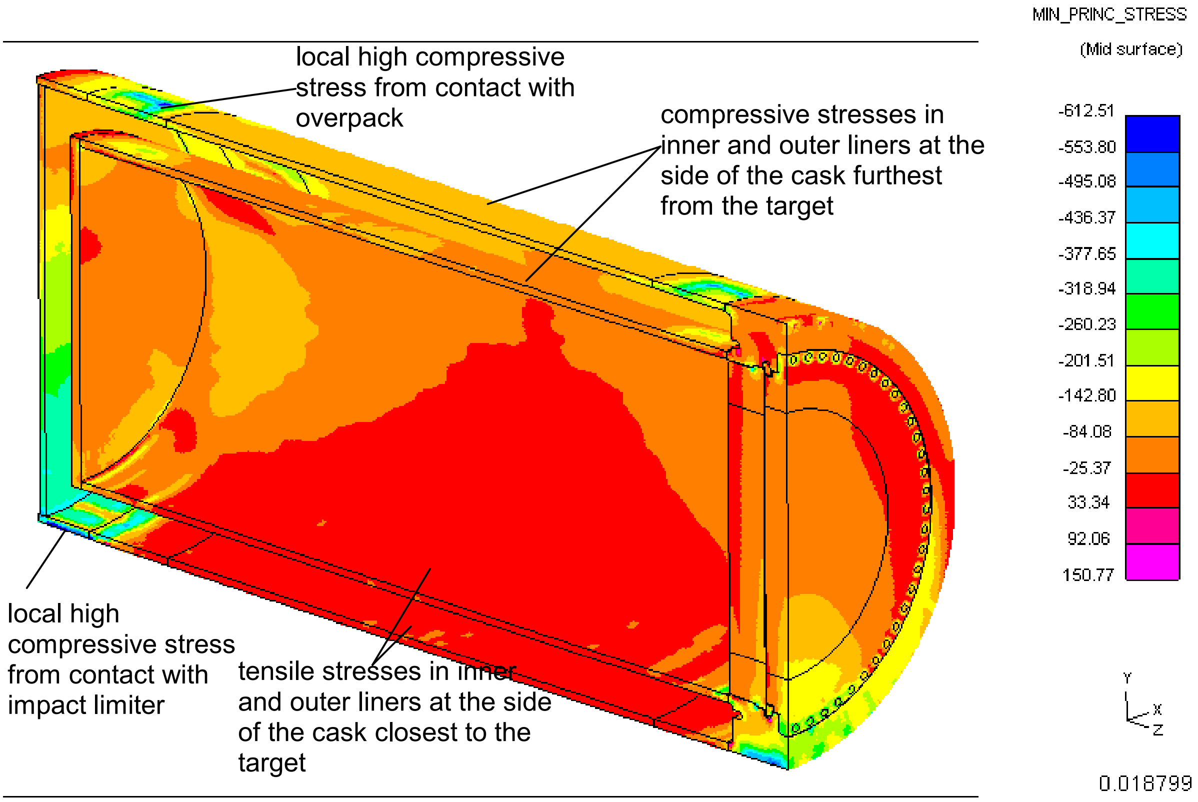

Fig. 4. General stress distribution in cask body during 9m Sidedrop.

The impact limiters contact the target first and started to decelerate. The cask and the overpack bear onto the impact limiters and also started to decelerate, crushing the impact limiters from the “inside”. As the cask bears onto the impact limiters, the wood becomes compressed and the partitioning plates buckle. The protection ring becomes ovalised and bent.

During the drop the cask deflects like a simply supported beam. It is supported at the top and bottom by the impact limiters. It is loaded along its length by its own inertial loading, the inertial loading of the upper half of the overpack and the inertial loading of the dummy basket. This causes the tensile stresses on the side of the cask closest to the target, and compressive stresses on the side away from the target. Localised stresses in the vicinity of the interfaces with the impact limiters, the overpack and the dummy basket are also seen.

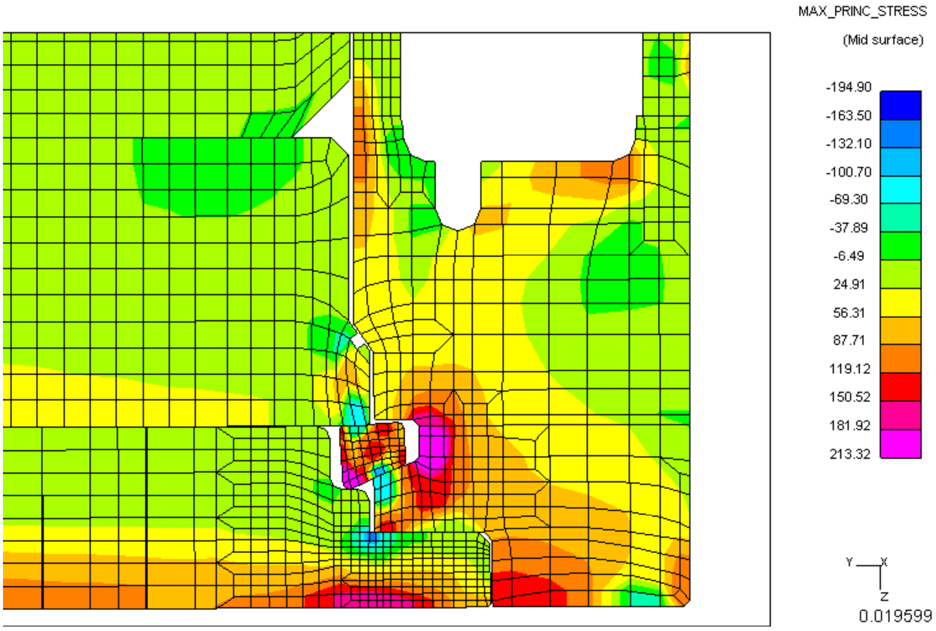

Fig. 5. Principal Stress (MPa) in Headring, Lids and Retaining ring during 9m Lid-Down drop

For all of the analyses performed, the overall performance of the package in terms of it's structural integrity was assessed generally by considering von Mises equivalent stress levels and plastic strain levels where yielding had occurred. The specific requirements of ASME [3] were also considered where stress distributions through a section must be linearised and decomposed into bending and membrane components. The assessment against ASME was performed for components that comprise the cask containment boundary, i.e. inner liner, headring, lid closure system and associated bolts.

The general assessment of von Mises stresses and plastic strains showed that for all drop cases;

- The stresses in the bolts stayed below yield.
- Although the stresses exceeded yield in certain locations within the headring, inner liner and secondary lid, the plastic strain values were small and significantly lower than failure strain of the material.
- The plastic strains were in general local

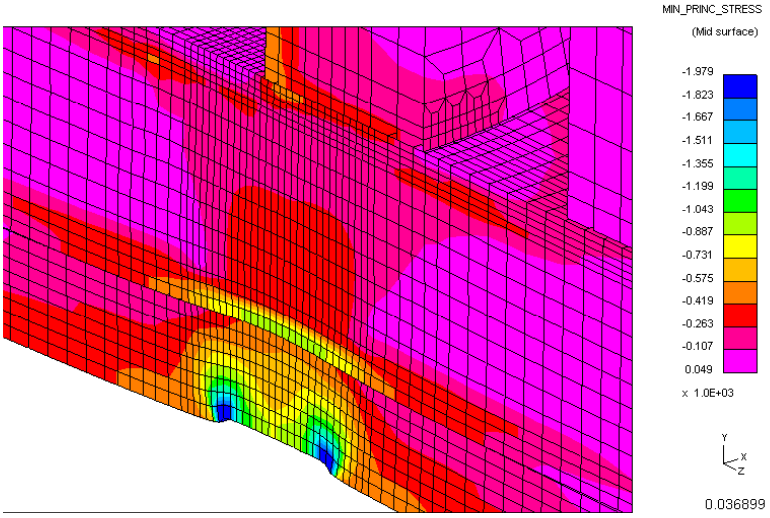

Fig. 5. Principal Stress (MPa) in Overpack, Outer Liner and Concrete during 1m Drop onto Punch

The maximum von Mises stresses and plastic strains show that the integrity of the containment will not be compromised during any of the drop scenarios analysed.

Stresses were assessed against the ASME [3] requirements in both the axial and circumferential directions of the inner liner, and in hoop and radial directions in the lids and the base of the inner liner. The locations at which stresses were evaluated were chosen to encompass the largest stress in the containment, including local stresses.

All of the predicted stresses in all of the drop scenarios fall below the limits required by ASME [3], with the exception of the primary bending stress intensity in the 1m side punch drop without the overpack. This demonstrates the need for an overpack. With the exception of the 1m side punch drop without an overpack, the integrity of the containment was demonstrated by evaluation against the appropriate ASME [3] limits.

5. Conclusions

The following conclusions were drawn from the work presented in this paper:

- Although the drop orientations analysed do not constitute all the possible orientations that the package can be dropped in, for either the 9m drop or the 1m punch drop scenarios; the analyses do suggest that the drop orientations analysed bound the behaviour of the cask.
- Integrity of the containment was demonstrated by evaluation against the requirements of ASME. All the stresses in all the drop scenarios stayed below the limits, with the exception of the primary bending stress intensity in the 1m side punch drop without the overpack. This demonstrates the requirement for an overpack.
- The integrity of the containment was also assessed by von Mises stresses and plastic strains. Stresses exceeded yield in certain locations in the headring, the secondary lid and the inner liner, although they were localised.
- The primary lid was effective in preventing any inertia loading from the contents from directly bearing onto the secondary lid.
- The protection plates and protection rings were effective in limiting the loading onto the cask from the punch impacts.
- The drop scenarios selected for the drop test programme are the worst case scenarios and bound the behaviour of the package

Furthermore it can be said that all of the objectives for the finite element analyses have been met.

6. References

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[1] Versuchs- und Messprogramm zum Nachweis des mechanischen Verhaltens des Testbehälters CONSTOR® V/TC unter Fallprüfbedingungen, GNB B 257/2003

[2] LS DYNA, version 970, Livermore Software Technology Corporation

[3] ASME Boiler and Pressure Vessel Code Sec 3 Div 3, 2004