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DEMONSTRATION OF THE IMPACT PERFORMANCE OF THE GRAVINER FLASK

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ABSTRACT

The United Kingdom Atomic Energy Authority (UKAEA) was formed in 1954 when the British Government set up a new body to oversee the nation's nuclear research programme. UKAEA's role was to provide Britain's atomic weapons deterrent and develop reactor technologies for the nuclear power stations of the future. Today, UKAEA is an internationally respected expert in nuclear clean-up, offering complete solutions in a wide range of services including programme management, decommissioning, waste management, environmental services and technical consulting.

The Graviner flask is a vertical loading flask for the transport of inventories in sealed cans between buildings on the UKAEA Harwell site. It has been in service in various forms for a number of decades.

Performance in hypothetical drop accident conditions form part of its performance requirements. A recent evaluation has shown that its performance has a number of shortfalls which would lead to loss of its safety function in such accident conditions.

One of the problems, however, was with the conservatism in the hand calculation method which was employed in the evaluation. This paper presents the work carried out to demonstrate the performance of the flask using the finite element method. This paper will present the details of the modelling and discuss the real behaviour of the flask.

INTRODUCTION

The United Kingdom Atomic Energy Authority (UKAEA) was formed in 1954 when the British Government set up a new body to oversee the nation's nuclear research programme. UKAEA's role was to provide Britain's atomic weapons deterrent and develop reactor technologies for the nuclear power stations of the future. Today, UKAEA is an internationally respected expert in nuclear clean-up, offering complete solutions in a wide range of services including programme management, decommissioning, waste management, environmental services and technical consulting.

The Graviner flask is a vertical loading flask for the transport of inventories in sealed cans between buildings on the UKAEA Harwell site. It has a modular construction consisting of, from the bottom, a Door Unit Housing which accommodates a two piece Gamma Gate, a Unit Barrel, a Half Unit Barrel, and a Shield Plug, all connected by sets of bolts. Sealed cans are loaded into the Graviner through the base via manually operated Gamma Gates by an electric hoist mounted on the Hoist Assembly at the top of the flask. The flask is transported vertically on a conveyance bed with tie-downs and chocks. It has been in service in various forms for a number of decades.

Performance in hypothetical drop accident conditions form part of its performance requirements. It is required to maintain its shielding integrity so that radiation level would not be increased by more than 20% on any external surface of the package.

In a recent evaluation in re-licensing of the Graviner flask for continuing service, a number of shortfalls in its impact performance were identified. The reviewers concluded that in the vertical down orientation, the flask would suffer a shock wave effect and its bolts would overload and fail, and in a number of other drop orientations, the bolted connections would suffer a combination of shear and tensile failures and therefore shielding integrity cannot be guaranteed.

The reviews were carried out by hand calculations with engineering judgement and reasoned arguments. An assessment of the reviews indicated that some extremely simplistic assumptions regarding load sharing, mode of deformation, and definition of "failure" were used. Such assumptions, when used together, produced a completely unrealistic understanding of the flask's behaviour.

In order to understand the real behaviour of the flask and to demonstrate that the flask can actually perform satisfactorily, drop tests or impact analyses could be carried out. However, only one flask was available for drop testing and therefore only one of the drop scenarios can be tested. In the event that the flask actually performs inadequately and modifications are required, a new flask would be required for additional drop tests. The cost of building a new flask at this stage of its service was deemed impractical. Analysis, on the other hand, would provide a much better understanding of the flask's behaviour and a much more thorough evaluation of its performance than could be obtained from drop tests. Once the model has been built, additional drop scenarios can be analysed with ease, and if design modifications are required, they can easily be incorporated. The drawback, however, is that analyses are only mathematical models of the reality. After careful consideration, UKAEA decided on demonstrating the performance of the Graviner by FE analysis.

This paper summarises the work carried out to demonstrate the impact performance of the Graviner in 1.2m drop scenarios and presents the evaluation of the base end edge drop and the vertical (flat bottom) drop.

DEMONSRATION OF PERFORMANCE IN THE BASE END EDGE DROP

Description of the model

The model is shown in Figure 1. It consisted of the entire flask, and was made up of 120000 solid elements, 26000 shell elements, organized into 99 parts.

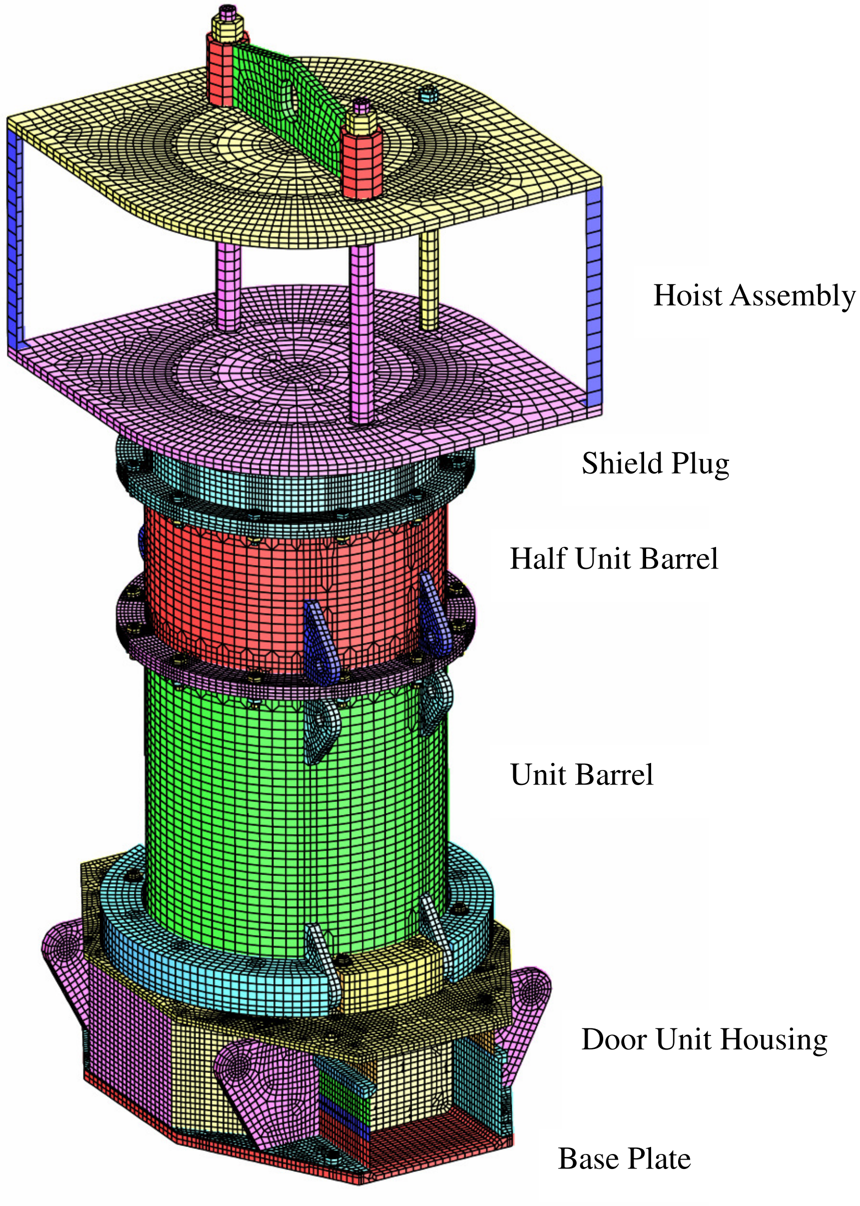


Figure 1 – FE Model of the Graviner

The principles that governed the design of the mesh can be summarised as follows:

- The mesh was refined at areas of higher stress gradients and deformation gradients, and also at locations where a higher level of accuracy was required. This included the end edge area of the Door Unit Housing and the Base Plate which would deform significantly, all the interfaces between the units, areas around the bolted connections and the welded connections.

- As far as possible, an identical mesh was used for identical components loaded with similar loadings – e.g. all the bolts around the same connection – so that the same "accuracy" can be attributed to all. For the same reason, an identical mesh was used for repeating geometries.
- The meshes on curved geometries of adjacent components that could contact during the impact were modelled to "match up" to avoid irregular stress patterns due to mesh mismatch during contact.
- In general, except for the bolted connections, shells were used instead of solids where the thickness of the section meant that if solid elements were used, a large number of small elements would need to be used and would control the timestep unless significant mass-scaling was employed.

Stress-strain behaviour of all the components were modelled as bi-linear elastic-plastic with isotropic hardening.

The whole flask was modeled explicitly except that the hoist motor was represented by a lumped mass.

All the bolts and studs were modelled using fully integrated solid elements with 12 elements in the shank cross section and 8 elements around the perimeter. This refinement has been found by experience to provide sufficient accuracy with acceptable element size considering the sizes of bolts in the Graviner and for the expected loadings during the impact events. Stress-strain behaviour was modelled as bi-linear elastic-plastic with isotropic hardening based on minimum properties as defined in the standards. Material failure by element deletion was defined for all the bolts and studs. The failure criterion was based on the plastic strain exceeding the true ultimate strain, derived from the elongation to failure of the material. The use of minimum properties, bi-linear stress strain behaviour and failure strain based on elongation to failure were all conservative assumptions, and the bolts in reality can be expected to have a higher ductility and strength than those modelled.

The analysis was executed in two phases – a dynamic relaxation phase followed by a transient phase. During the dynamic relaxation phase, bolt pre-force due to tightening torque was applied to obtain the required pre-stress in the bolts, studs, nuts and adjacent components, which then became the initial condition in the transient phase. The model was located close to the target in the CG over base short edge orientation and it was given an initial velocity of 4.852 m/s perpendicular to the target, representing the impact velocity after a drop from 1.2m.

The analysis was carried out using LS-DYNA 970v5434 installed on HP Itanium II platforms.

Discussion of the flask behaviour

The reviewers postulated that all the bolts connecting the base plate to the door unit housing would fail by shear and the gamma gates would be released. The door pins which maintain the gamma gates within the Door Unit Housing would also fail by shear as the Gamma Gates ramp forward.

Deformation behaviour of the flask is shown in Figures 2 and 3. Deceleration-time history of the event (with deceleration in mm/s² and time in seconds) is shown in Figure 4.

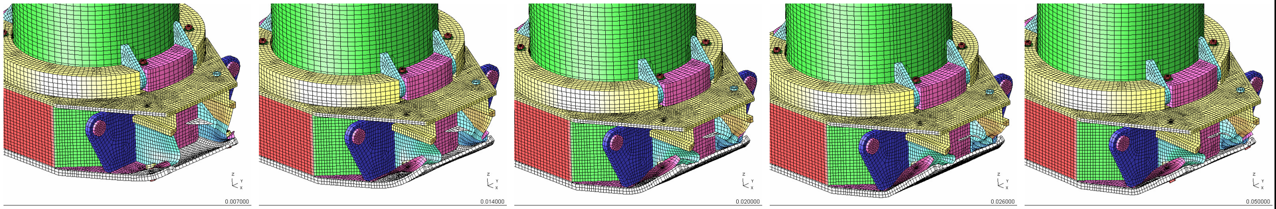


Figure 2 – Deformation of the Graviner as impact progressed

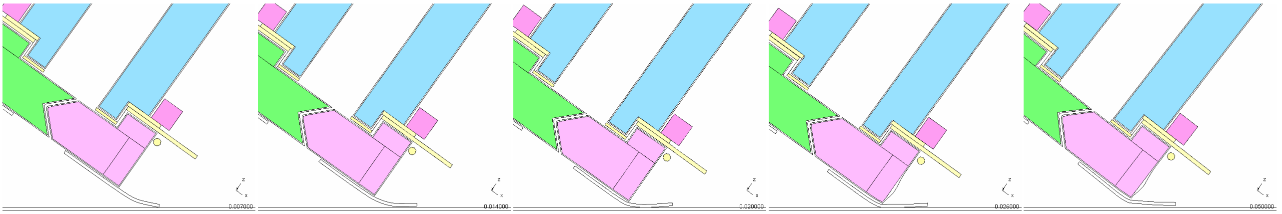


Figure 3 – Deformation behaviour of the Graviner through the symmetry cross section

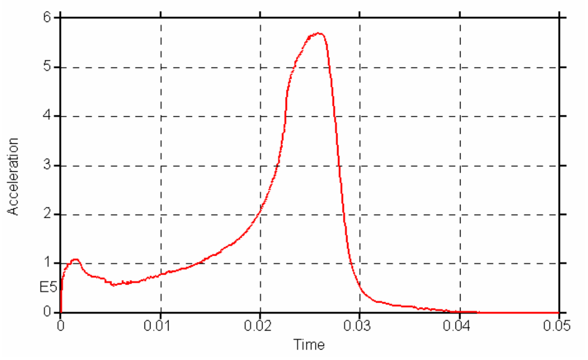


Figure 4 – Deceleration-time history

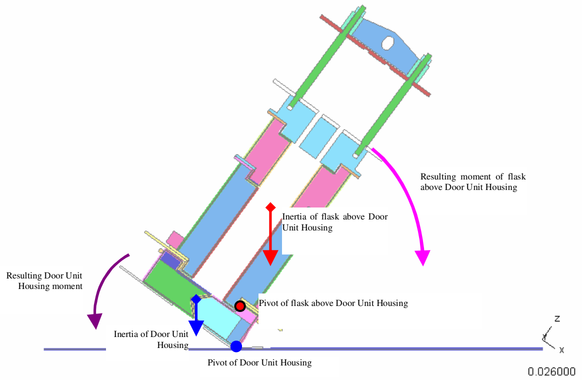


Figure 5 – Illustration of the overall behaviour

The Base Plate made first contact with the target. Reaction from the target consisted of a component parallel to the plane of the Base Plate, and a component perpendicular to it. The former was reacted by the friction at its interface with the base of the Door Unit Housing and by shear in the bolts that connect it to the Door Unit Housing. The latter caused the side plates of the Door Unit Housing to buckle and the Base Plate to bend. The drop in deceleration at about t=2ms corresponds to the onset of this buckling.

As knockback progressed, the area of the Base Plate that came into contact with the target enlarged, the width of the Base Plate that needed to be bent widened, and the extent of buckling in the side plates increased. These account for the increase in the rate of deceleration from t=5ms to about t=16ms in Figure 4.

The continuing bending of the Base Plate and the base of the Door Unit Housing caused "shear" at their interface and this caused the bolts that connected the two to fail as they came into the knockback area. The small drop in deceleration at about t=5ms corresponds to failure of these bolts.

The knockback reached the right Gamma Gate at about 14ms. It was loaded at its base end edge by the bent Base Plate. It was pushed upwards to jam onto the top of the Door Unit Housing, and in the negative X direction to bear onto the recess of the Door Unit Housing. Its base end edge was slightly knocked back as it was further compressed.

Knockback reached the Lifting Lug of the Door Unit Housing soon after it reached the right-hand section of the Gamma Gate. This is significantly stiffer than any of the structure that has been knocked back so far. The Base Plate that had already been bent (i.e. curved) started to flatten against the target from about t=14ms to t=22ms. Then the structure further stiffened as the Base Plate had "locked up" against the Lifting Lug. The remaining impact energy was absorbed over small deformations, and hence a correspondingly steep increase in deceleration from around t=22ms as shown in Figure 4.

The global behaviour of the flask is illustrated in Figure 5. For the Door Unit Housing, the offset between its centre of gravity and the reaction from the target tended to rotate it to slap down onto the target at its base. For the assembly of the Unit Barrel, Half Barrel and Hoist Assembly, the offset between their CG and the reaction at the contact with the Door Unit Housing, tend to rotate them to slap down onto the side of the flask. The rotations in opposite directions in the Door Unit Housing on the one hand, and the units above it on the other, generated a "prying" action on stud-nut connection at the Unit Barrel - Door Unit Housing interface, loading the studs at the far end of interface in tension.

This behaviour created compressive loadings in the front half of the Unit Barrel and the Half Unit Barrel, and tensile loadings on the back, as shown in Figures 6 and 7. Similarly, this created compressive loadings on front area of the Door Unit Housing and tensile loadings at the far end away from the target, as shown in Figures 8 and 9.

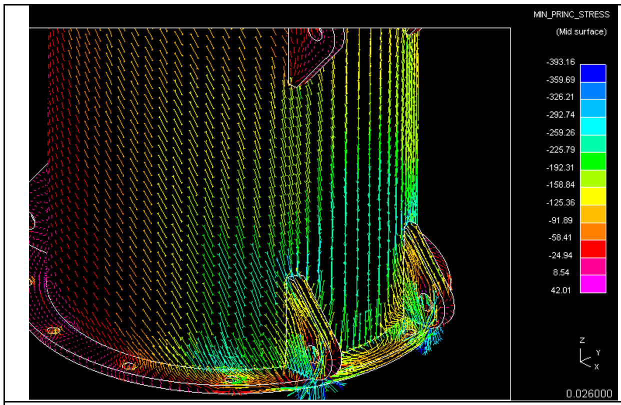


Figure 6 – Compressive load path in the Unit Barrel

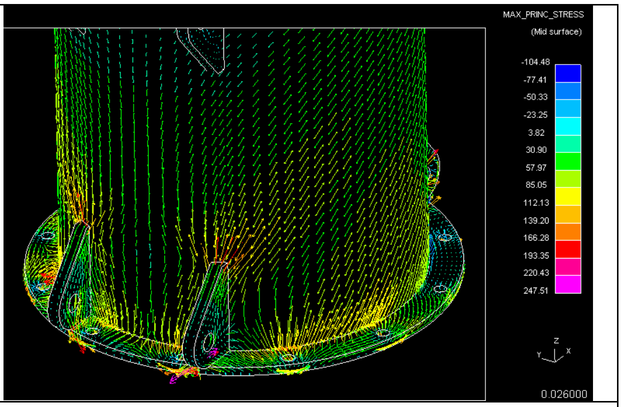


Figure 7 – Tensile load path in the Unit Barrel

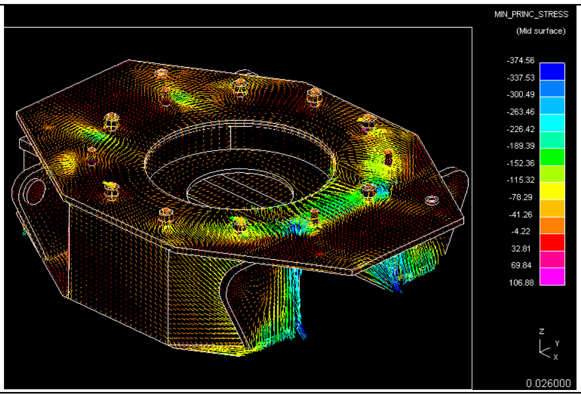


Figure 8 – Compressive load path in the Door Unit Housing

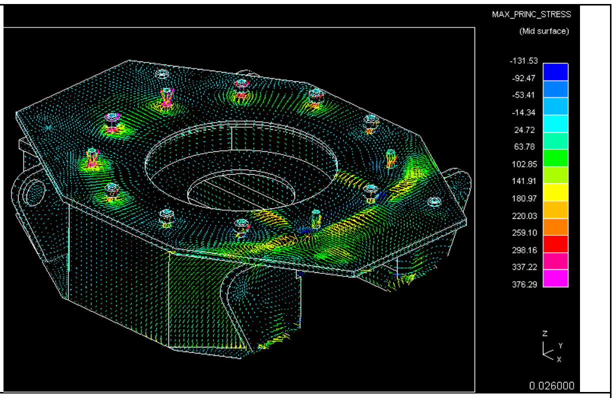


Figure 9 – Tensile load path in the Door Unit Housing

Evaluation of integrity

Performance criteria of the flask is based on its shielding performance and plastic strains is an indirect mean to assess the integrity of the shielding. So, in this assessment, plastic strains were not evaluated on their own as a pass/fail criterion of flask performance, but in the context of their effect on the integrity of the shielding. For example, plastic strains exceeding the failure strain at Point A on the flask would not lead to the conclusion that "the flask has failed", but would lead to further question as to whether shielding integrity is affected. If shielding integrity is not affected, exceeding the failure strain at Point A has no effect on the performance of the flask.

Integrity of the components that maintain shielding was evaluated by comparing the plastic strains predicted by the analysis with failure strain of the material. Failure strain was based on the true ultimate strain derived from elongation to failure of the material. All the welds regardless of their configuration were assessed against a failure strain that is half the value of the failure strain of the parent material to account for the lower ductility of the weld material. Overall integrity of each set of the bolted connection would be evaluated by assessing the number of failed bolts in the connection and the plastic strains in the remaining bolts/studs.

The highest strains in the Door Unit Housing and the Base Plate were found in the area that crushed during the impact. Evaluation of the extent of areas in the rest of the structure in which the failure strains were exceeded, indicated that none of the failures has any effect on the shielding performance.

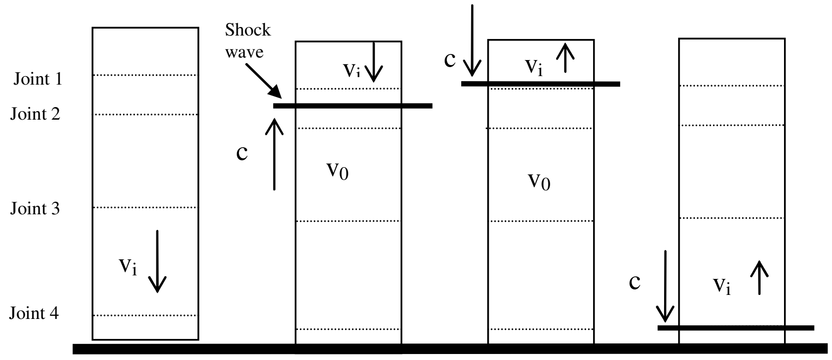
Plastic strains in all the bolt/stud connections, besides the two Base Plate to Door Unit Housing bolts that failed, stayed below the failure strain with a minimum reserve factor of about 1.5.

It was therefore concluded that the Graviner flask would perform satisfactorily in a 1.2m drop in the base end edge orientation.

PERFORMANCE IN THE AXIS VERTICAL DROP

Review of the shock wave argument

Failure by shock wave effect has been postulated in the past as the failure mechanism of a number of flasks which do not have impact limiters. The argument put forward by the reviewer of the Graviner is illustrated in Figure 10 below:



Flask impacts the target with velocity v_i

Shock wave from the impact travels upwards at the speed of sound (c) bringing the flask elements to rest (v_0) as it passes

Shock wave reflects at the top of the flask and travels downwards at the speed of sound, relieving the stress in the flask elements as it passes allowing them to move upwards with velocity v_i

Flask rebounds from the target when the shock wave reaches the bottom of the flask, i.e. the whole flask has been relieved to move at v_i.

Figure 10 – Summary of the shock wave argument

The reviewer also postulated the following: As the shock wave passes through a flask joint after it has reflected from the top of the flask, the bolts at that joint are subjected to tension as the units above the joint has already been relieved and moving with velocity v_i upwards while the units below the joint are still stationary at v_0.

There are a number of simplifications in the argument which make the argument unrealistic and extremely pessimistic:

1) Since the theory assumes that the flask rebounds with the velocity of impact, it implicitly assumes no energy loss and no permanent energy absorption in the event. But it also assumes that, as the shock wave passes through a flask joint after it had reflected from the top, all of the kinetic energy of the flask units above the shock wave has to be absorbed by the bolts in that joint, i.e. assuming that there is to be no rebound of the units below the joint. Obviously, these two assumptions are incompatible.

2) The shock wave velocity c will be significantly higher than the impact velocity v_1 (the ratio is likely to be about 1000). Any plastic deformation of the bolts (i.e. stretching of the bolts due to the differential velocity of the connected units) will only take place at speeds comparable to the impact velocity v_1. If plastic deformation is to take place, shock wave magnitude will be significantly reduced since shock wave can only propagate properly if the material remains elastic. The theory does not take this into account and conservatively assumes that the shock wave propagation is unaffected by plastic deformations.

3) The calculation assumes that each joint absorbs all of the kinetic energy of the unit above the joint with the unit below it effectively fixed to the ground with infinite inertia. This assumption is extremely pessimistic.

Real behaviour of the flask in this scenario

In order to understand the real behaviour of the flask in this scenario and to evaluate its performance, FE analysis of the Graviner in this scenario was carried out. The model described above for the base end edge drop was used except that the lead shielding was given stress strain properties of steel to create the worst context for shock wave effect to occur.

Snap-shots of the flask during the event with vertical velocity contours (in mm/s) are shown in Figure 11.

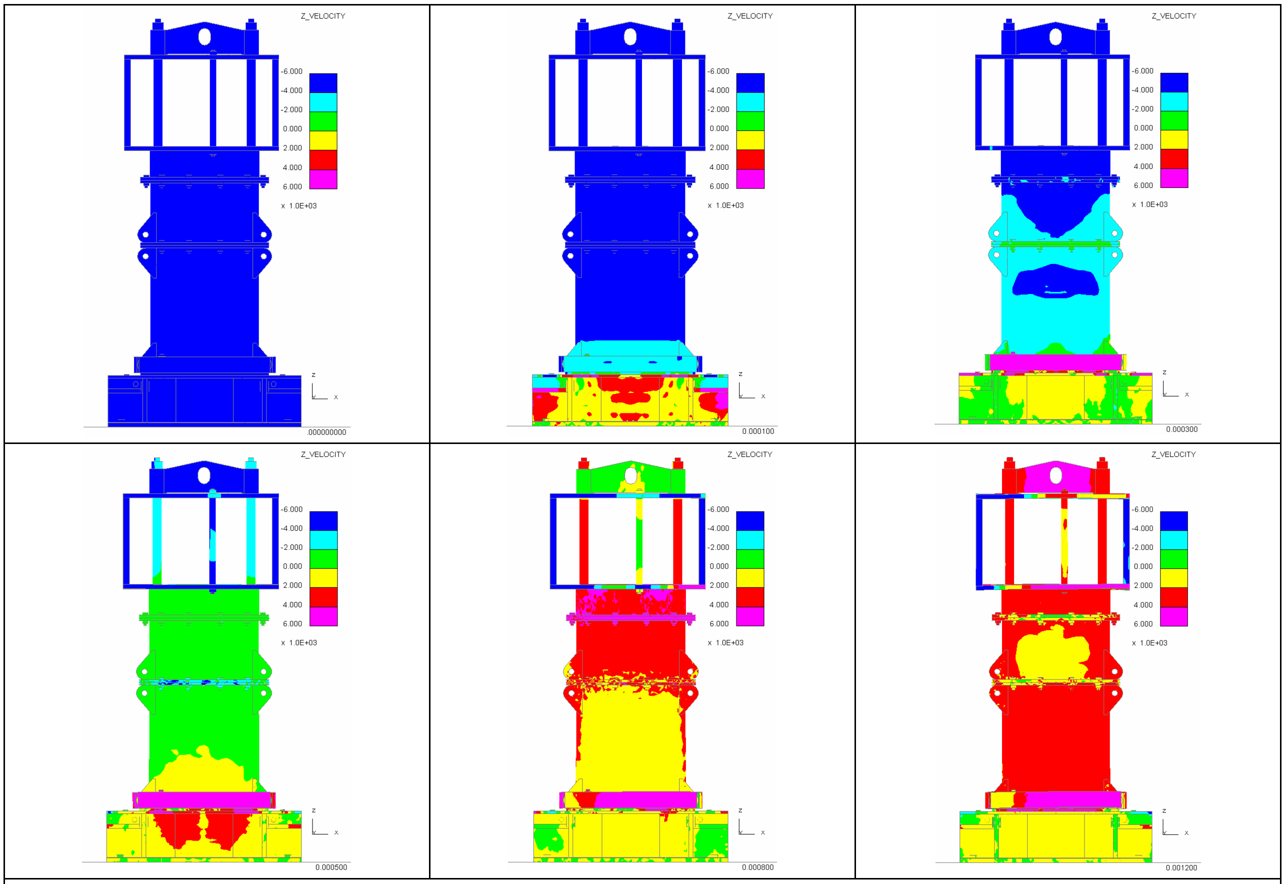


Figure 11 – Snap shots through the event showing vertical velocity contours

The event can be described as follows:

- At t=0ms, the flask made contact with the target at the initial impact velocity of 4852mm/s
- At t=0.1ms, the Door Unit Housing had come to rest.
- At about t=0.2ms, the Unit Barrel had started to slow down.
- At about t=0.5ms, the Unit Barrel had largely come to rest and soon after, the Half Unit Barrel and Plug came to rest before rebounding immediately.
- At about t=0.8ms, the Unit Barrel was already in rebound and the Door Unit Housing started to rebound, although parts of the Hoist Assembly still had not slowed down significantly.
- At about t=1.2ms, the whole flask had rebounded and lifted off from the target. However, due to the relative flexibility of the hoist assembly, parts of the Hoist Assembly were still moving towards the target.

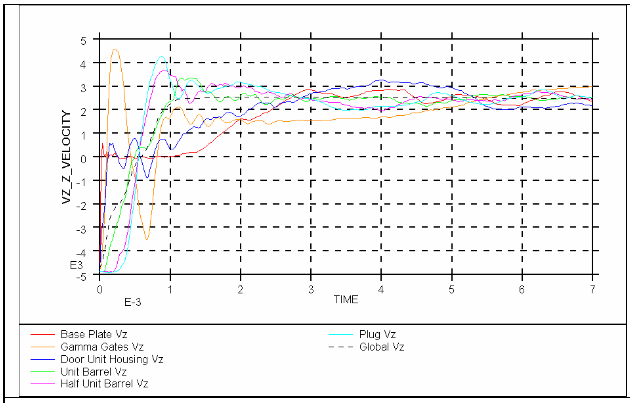


Figure 12 – Vertical velocity time history of key components

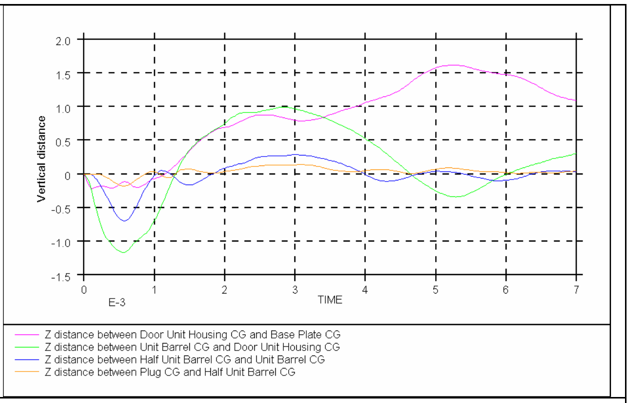


Figure 13 – Time history of distance between CG of key components

Vertical velocity time histories (with velocity in mm/s and time in seconds) of the different units of the flask measured at their centre of gravities are shown in Figure 12. It shows clearly the timing at which the different units started to slow down - Base Plate, followed by the Door Unit Housing, then the Unit Barrel, then the Half Unit Barrel and finally the Plug. It also shows the order of rebound – Plug, followed by the Half Unit Barrel, then the Unit Barrel, then the Door Unit Housing and finally the Base Plate. As the Gamma Gates are “loose” and not rigidly connected to the rest of the structure, it bounced within the cavity within the Door Unit Housing rather independently from other components. However, because it was resting on the Base Plate, it had to be lifted by the Base Plate when the flask rebounded. The effect of this is seen in the big lapse in the timing of the rebound of the Base Plate and the delay in the Gamma Gates catching up with the rest of the flask. The graphs also show that some energy was “lost” during the impact as the rebound velocity was only half the impact velocity.

Relative distance between the key components measured between their centre of gravities (i.e. including overall compressions and flange deflections) are shown in Figure 13. It shows the centre of gravities of the key components compressing against each other as the flask came to a stop, with the largest compression happening between the Unit Barrel and the Door Unit Housing which deflected most significantly at their interface due to their geometry. It shows also the stretching between the key components as they rebound. In all cases except the distance between Door Unit Housing to Base plate, the extension was smaller than the compression during the impact, i.e. there were slight plastic deformation in the units during the impact. The stretch between the centre of gravities of the Base Plate and the Door Unit Housing again reflect the deflection of the Base Plate as it pulled the Gamma Gates towards the rest of the structure.

In overall terms, each unit of the flask was compressed by its own inertia and the inertia of the units above them as it bore onto the target or the unit below it. It came to rest as it reached maximum compression under the loading exerted on it. It tried to rebound as soon as it came to rest but restrained from this by the unit above it, but as the top unit rebounds, the unit below it was released to rebound, and so on.

Figures 14 and 15 show Von Mises stress distribution and minimum principal stress distribution (i.e. compressive load path) (both in MPa) at a typical time of 0.5ms through a vertical cross section of the flask to illustrate the compressive behaviour in the flask.

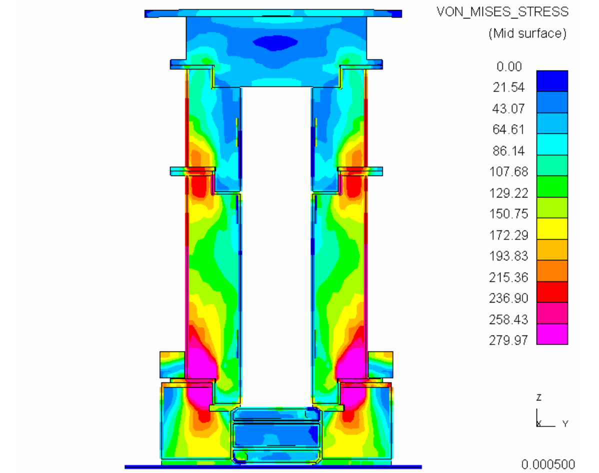


Figure 14 – Von Mises stress distribution through a section at a typical time

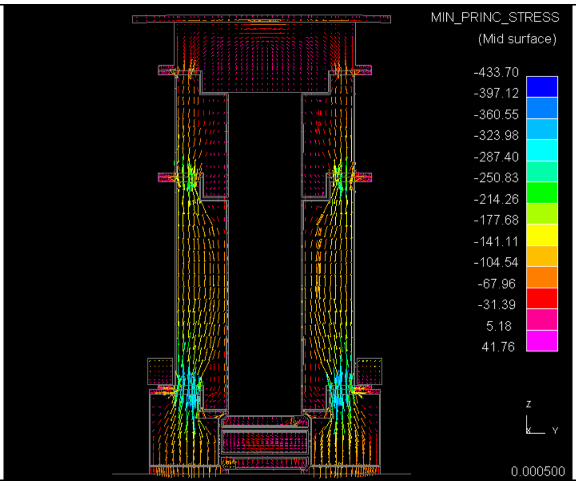


Figure 15 – Compressive load path through a section at a typical time

Axial force of each set of bolts is shown in Figure 16. In the studs connecting the Unit Barrel to the Door Unit Housing, the initial pre-stress of about 320kN reduced slightly during the compression, oscillated during this time, and as the units rebound, the force increased, reaching a peak of about 630kN at about 26ms. The bolts connecting the Unit Barrel to the Half Unit Barrel and the bolts connecting the Half Unit Barrel to the Plug reduced during the initial compression and then recovered as the components rebound, and continued to oscillate as the flask rebound continued. The bolts connecting the Base Plate to the Door Unit Housing compressed and then stretched as the Base Plate pulled the Gamma Gates towards the rest of the flask as the flask rebounded. The delay in the timing of the peak is consistent with those already seen in Figures 12 and 13.

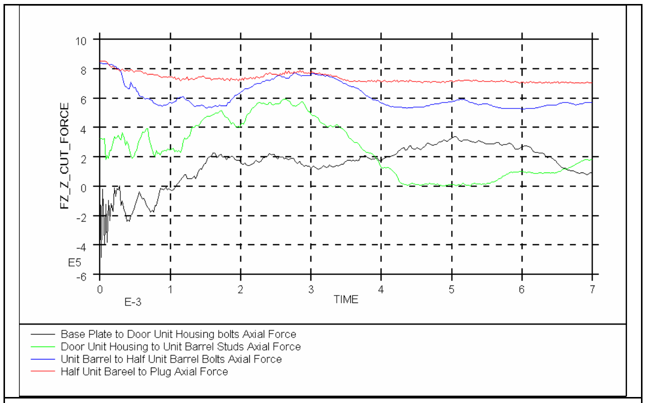


Figure 16 – Bolt/stud axial force time history

Evaluation of integrity

Plastic strains in the plates and welds of the main Flask components (the Base Plate, Door Units, Door Unit Housing, Unit Barrel, Half Unit Barrel and the Plug) all stayed below the failure strain with a minimum reserve factor of about 1.5, except in the Door Units where the minimum reserve factor is about 1.1.

Plastic strains in all of the bolt/stud connections, except for the Door Unit Housing to Unit Barrel studs, were very low and stayed well below the material failure strain. Of the Door Unit Housing to Unit Barrel studs, two of them which secured the large shielding segments failed. However, the loss of these shielding segments will not significantly affect the shielding performance of the flask. Besides these two studs, most of the studs had a relatively high level of plastic strain although the values were still comfortably below the failure strain.

CONCLUSIONS

The work has shown the real behaviour of the flask and demonstrated that the flask would perform satisfactorily in the 1.2m drop onto a flat unyielding target. It has shown that the behaviour of the flask in the vertical drop can be explained by usual impact dynamics terminology and that a shock wave tensile load in bolts of the order originally postulated is not apparent even when the material properties are optimised for such an effect.

Based on the analyses, the Nuclear Installation Inspectorate granted continued operation of this flask for a further 2 years until its retirement later this year.