Proceedings of the 18th International Symposium on the
Packaging and Transportation of Radioactive Materials
PATRAM 2016
September 18-23, 2016, Kobe, Japan

Paper No.
5030

Innovative Waste Packaging and Associated Venting/Hydrogen Management

Conrad Izatt
Arup

Daniel Fisher
Croft Associates Ltd

Chris Chadwick
Porvair Filtration Group

Abstract

The original strategy for managing intermediate level waste (ILW) was developed in the 1980s by the UK Nuclear Industry Radioactive Waste Executive (NIREX), which is now the Radioactive Waste Management Limited (RWM), a wholly owned subsidiary of the Nuclear Decommissioning Authority (NDA). The strategy involved retrieving ILW, sorting and encapsulating it in cement based grout within thin walled stainless steel containers. The containers would then be transferred to a large purpose built shielded ILW store, where they would be stored until the planned deep geological disposal facility becomes available.

In recognition of the high up-front costs of such a strategy, which requires remote facilities for the encapsulation and storage, and coupled with the long programme duration for the design, construction and commissioning of these facilities, waste management organisations responsible for managing the clean-up of legacy facilities within the UK have, in recent years, sought innovative solutions which could potentially accelerate clean-up and hazard reduction on sites, and with a lower overall programme lifecycle cost.

Many of the recent innovative solutions are focused around a new family of packaging designs known as Robust Shielded Containers (RSCs). These are self-shielded containers manufactured from materials such as ductile cast iron or fabricated steel.

The paper provides a high level overview of the generic concepts of RSCs developed by Croft and focuses on the specific challenges of wasteform evolution on waste package integrity and performance. In particular, the integrity and performance of the filtered vent system required to manage internal pressurisation and to ensure sufficient venting capacity of hydrogen and other evolved gases.

The paper summarises the analysis by ARUP undertaken to substantiate the RSC integrity under detonation/deflagration explosion loadings arising from hydrogen accumulation. Analyses of the structural response of the filter assembly were undertaken for both detonation and deflagration explosion scenarios, with the loadings applied to the filter housing rim and to the filter vent cover.

The paper also presents evidence of the mechanical performance of the filter medium in terms of pressure transients during deflagration events and the degree to which filtration efficiency is maintained.

Introduction

In the 1980s the UK Nuclear Industry Radioactive Waste Executive (NIREX), which is now the Radioactive Waste Management Limited (RWM), a wholly owned subsidiary of the Nuclear Decommissioning Authority (NDA), implemented a strategy to manage intermediate level waste (ILW) by retrieving, sorting and encapsulating ILW in cement based grout. The waste package would then be transferred to a large purpose-built ILW store on site, where they would be stored until the planned final deep Geological Disposal Facility (GDF) becomes available.

Traditional waste packages fall into two broad categories of unshielded and shielded waste containers, the choice depending on the form of material to be packaged; both categories required the waste to be encapsulated in a cement based matrix. Unshielded ILW containers are thin walled stainless steel containers and when packaged with radioactive waste require remote handling in heavily shielded facilities and transport flasks. Shielded ILW containers are used traditionally for packaging low dispersible materials such as Low Specific Activity (LSA) or Surface Contaminated Objects (SCO) items, and are designed as Industrial Packages for transport in the public domain [1]. Various options have evolved for packaging low dispersible materials comprising early designs of reinforced concrete boxes and improved designs of stainless steel boxes designed to ISO freight container standards and having a concrete lining placed inside for shielding. These shielded ILW containers can be stored in ‘simple’ stores that allow for controlled man access whereas unshielded waste packages require more highly engineered shielded stores with remote handling facilities. Containers using concrete for shielding also require a cementation plant to place the cement shield lid remotely after the waste has been encapsulated within.

In 2006 Magnox, working with the NDA, examined novel and innovative ways to accelerate decommissioning of its fleet of Magnox reactors which had reached the end of life. This concluded with Magnox introducing the concept of Robust Shielded Containers (RSCs) for the long term storage and eventual disposal of ILW. These RSCs are Ductile Cast Iron Containers (DCICs) which had been developed in Germany as ILW storage, transport and disposal containers by GNS. These containers were intended for wastes that were traditionally packaged in both unshielded and shielded ILW containers depending on form of material.

Robust Shielded Containers (RSCs)

To meet UK disposability requirements waste packages are expected to limit release of contents and limit shielding loss in accident conditions, this has traditionally been achieved by encapsulating the waste form. RSCs are designed such that the container alone with minimum demand on the wasteform meets the same accident conditions.

The RSCs offer advantages that include removing the need for a waste encapsulation plant that is integral to waste packaging operations. For what were traditionally called unshielded waste packages stored in heavily shielded buildings, RSCs offer opportunities for storing such wastes in much simpler stores. Thus offering additional potential benefits for significant savings to cost and programmes by eliminating the need for: heavily shielded stores, remote handling and heavily shielded facilities and transport flasks.

For shielded waste packages traditionally using concrete for shielding, ductile cast iron is a more efficient shield material (due to its higher density and atomic number). For the same external package volume and same shielding efficiency, a package made in ductile cast iron has a greater internal volume for the waste. This improved packing efficiency offers benefits of fewer handing operations, fewer containers, less transport operations, reduced environmental impact, and lower public and operator radiation exposure due to fewer operations.

RSCs also offer advantages for some problematic wastes that might be reactive in a cementitious environment.

By reducing the need for complex waste packaging plant and heavily shielded stores, the use of RSCs offers waste packagers the opportunity to achieve hazard reduction much more quickly and more economically than using the more traditional approaches to packaging wastes in the UK.

Safstores

Croft Associates Ltd (Croft) has developed a range of Robust Shielded Containers manufactured in ductile cast iron, known as Safstores (Illustrated in Figure 1) for the long term storage, transport, and disposal of certain types of Intermediate Level Waste (ILW). These Safstores are intended for a wide range of wastes that would traditionally have been packaged in shielded and unshielded containers; the containers can optionally include: twistlock corner fittings machined in the body for lifting and tie-down; separate lids for shielding and to provide verifiable containment for transport; process ports to allow conditioning of waste, and filter vents for gas management.

Waste packages have to meet varied requirements for operations during their lifecycle on different regulated sites, covering operations where the ILW is packaged and stored, transportation on-site and off-site, and lifetime storage at the final disposal site. Demonstrating that the Safstores can withstand the range of postulated accidents occurring during each phase of its life cycle is achieved by a combination of assessment, analysis and testing. Particular consideration is given to the resistance to drop accidents, cliff edge effects and the effects of gas generation as the wastes maybe stored in these containers for extended periods (up to 150 years prior to transport).

Prototype Safstores have been subject to Finite Element Analysis (FEA) for impact and thermal load cases, and subject to testing to benchmark the analytical models. The tests carried out included simulated accident conditions of a 9m drop in worst container orientation onto an unyielding surface, a 800^{O}C all engulfing fire test and a 0.5m drop onto an IAEA punch target orientated specifically onto a lid filter; test conditions were as prescribed by the IAEA Transport Regulations [1] with the exception of the 0.5m punch test which met a customer's onsite transport requirements.

Figure 1 - Robust Shielded Containers[1]

Some wasteforms may have a propensity for hydrogen generation which could be as a result of radiolysis of water contained in some wastes. Over extended periods of time this hydrogen may accumulate within the container and could potentially exceed the Lower Flammability Limit of 4% by concentration. At this concentration the presence of an ignition source (e.g. presence of pyrophoric materials) could cause a deflagration or detonation (depending on a range of factors) to occur within the container. In such accident conditions it is important for the Safstore to withstand and provide containment against any potential releases.

However in order to effectively manage gas generation, Safstores are fitted with filtered vents (Porvair TruVent) which regulate the build-up of pressure and allows the container to breath whilst preventing particulate release (99.7% > 0.3µm).

Case Study

In one case study, Croft included nine TruVents that provided a combined diffusivity rate of 1.65 $x10^{-4}$ moles/s/mol fraction hydrogen. For the proposed contents this would allow the Safstore to maintain a minimum 1% concentration; many technical standards within the UK industry recommend a safe working hydrogen limit of 1% and 4% under accident conditions.

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[1] Croft Associates Ltd products

Although confident that the probability of a deflagration/detonation event was low, as a contingency it was considered prudent to demonstrate the Safstore's ability to withstand and provide containment in the event of a potential deflagration/detonation.

The propensity and subsequent magnitude of a pressure pulse arising from a hydrogen deflagration event was the subject of much technical debate throughout the scope of work; based on the customers input the maximum deflagration pressure ratio obtainable (i.e. at the stoichiometric concentration) for a hydrogen oxygen concentration was determined to be 9.8 at room temperature (25^{O}C) and pressure (1bara). Assuming that an internal pressure of 2bara (1barg) existed within the Safstore the peak overpressure due to deflagration would reach 19.6bara (18.6barg), further calculations based on this overpressure lead to an estimated pulse duration of 50.2ms with pressure raising to a peak pressure at 25.1ms.

A similar stance was adopted in the case of a detonation event; a pressure spike resulting from an explosion was expected to be 18.6barg at 0ms and falling to 0barg at 50.2ms. Figure 2 shows the pressure profiles of both events.

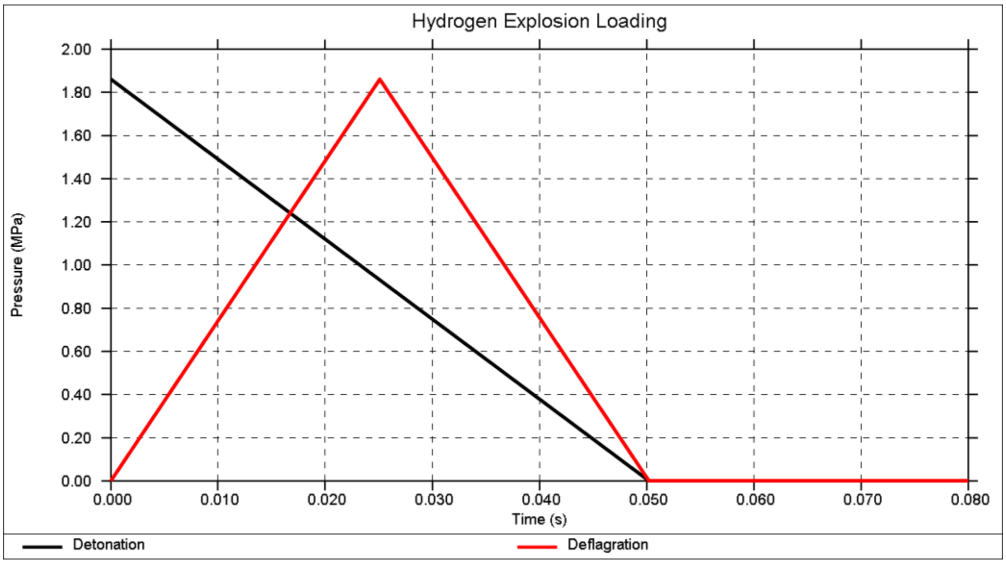

Figure 2 - Hydrogen explosion loading

In order to demonstrate the Safstore's capability to withstand this pressure pulse Croft approached Arup to undertake FEA modelling of a deflagration and a detonation event within a Safstore.

Structural Response to Explosion Loading

A non-linear dynamic analyses of the Safstore's structural response to explosion loading was carried out. The response of the Safstore was assessed in two parts:

i. Global analysis, to assess the integrity of the container as a whole.
ii. Local analysis, to assess the response of the hydrogen filter assembly in the Croft Safstore box lid to the explosion loading.

The explosion loading was modelled using pressure time histories previously discussed. The shape of the pressure pulse was unknown, but the profiles for the detonation and deflagration pressure pulses (Figure 2) were chosen because they are simple and commonly used approximations to realistic pressure pulses.

Finite Element Model for Global Analyses

The main objective of the global analyses was to determine the overall response of the Safstore to the explosion loading. Therefore, it was not necessary to model the contents of the box, the lid seal or the lid filter. The finite element model used for the global explosion analyses had been previously developed for preliminary impact analyses and is shown in Figure 3. The mesh design of the Box was suitable for the explosion analysis work. The body and lid were modelled using solid elements. The lid was bolted to the body using thirty-four M36 bolts, which were modelled using beam elements.

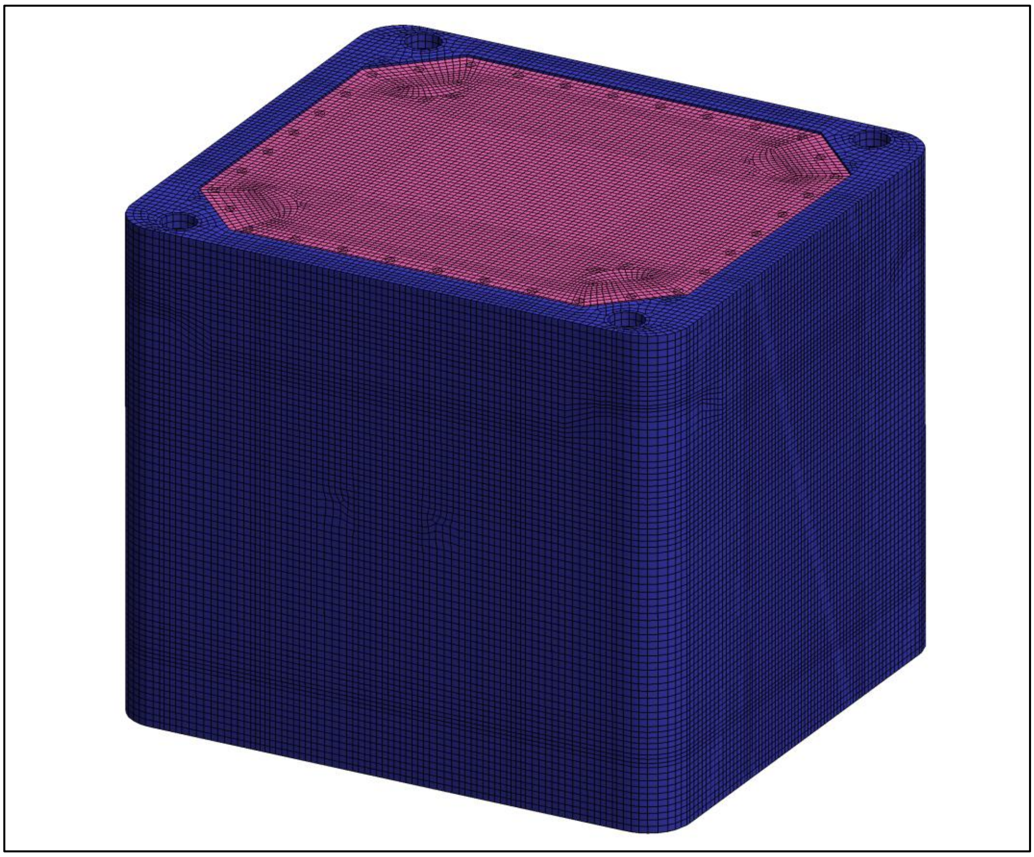

Figure 3 – Finite element model of the Croft Safstore box

Explosion Loading Applied to Box

Under the detonation blast loading there was no plastic strain in the Safstore body and lid (i.e. the Safstore remained elastic). There was a negligible amount of plastic strain in the lid bolts (less than 0.2%). Under the deflagration blast loading there was no plastic strain in the Safstore body, lid and bolts (i.e. the Safstore and bolts remained elastic).

The highest von Mises stress observed in the container body and lid from either the detonation or deflagration was approximately 102 MPa (compared to a yield stress of 240 MPa). A deformed view of the Safstore, magnified by a factor of 500, is shown in Figure 4 at a time of 1.5ms from the start of the detonation explosion to illustrate the deformation.

Overall, the Safstore is expected to maintain integrity under the detonation and deflagration explosion loading.

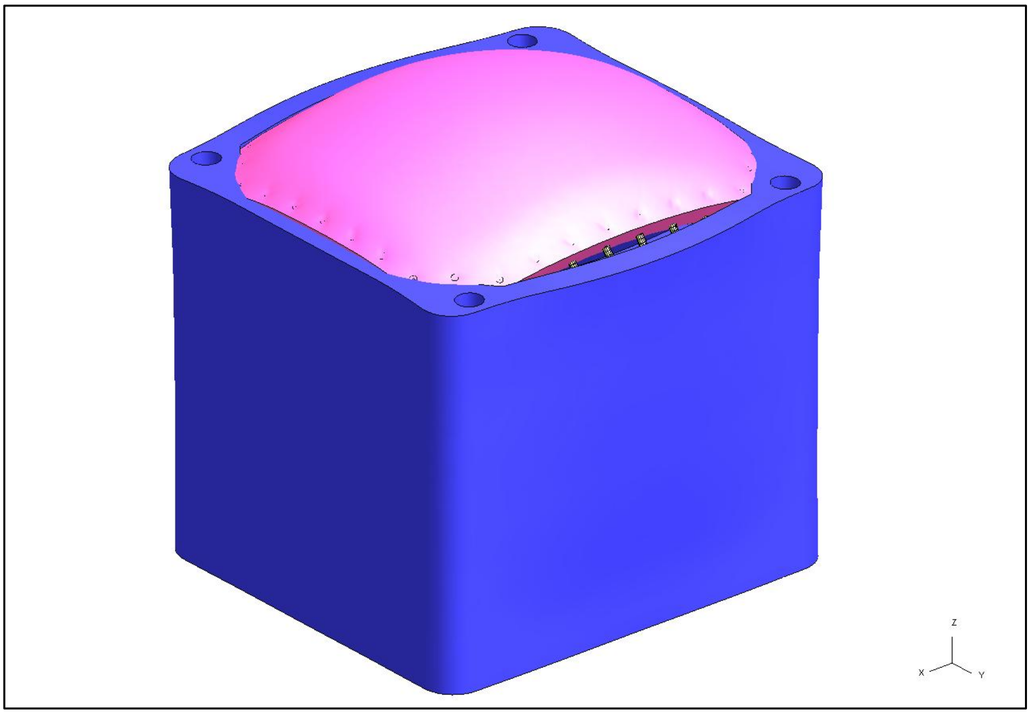

Figure 4 – Deformation of the Croft Safstore box, magnified by 500, at 0.0015 secs

Finite Element Model of the Filter Assembly

To calculate the effect of the blast pressure (detonation and deflagration) on the lid filter, a local component model of the lid filter was created and is shown in Figure 5 and Figure 6.

The flange was modelled using solid elements, while the filter housing and filter vent cover were modelled using thin shell elements. Note that it was not necessary to model the filter mesh itself, since the filter mesh had been shown to withstand the peak pressure from the explosion. The welds connecting the filter housing to the flange plate and the filter vent cover to the filter housing were modelled using beam elements. The bolts that connected the filter flange to the lid were not modelled explicitly and the nodes on the filter flange directly under the bolt heads were fully constrained. Simple hand calculations demonstrated that the stresses in these bolts due to the explosion pressure would be very small.

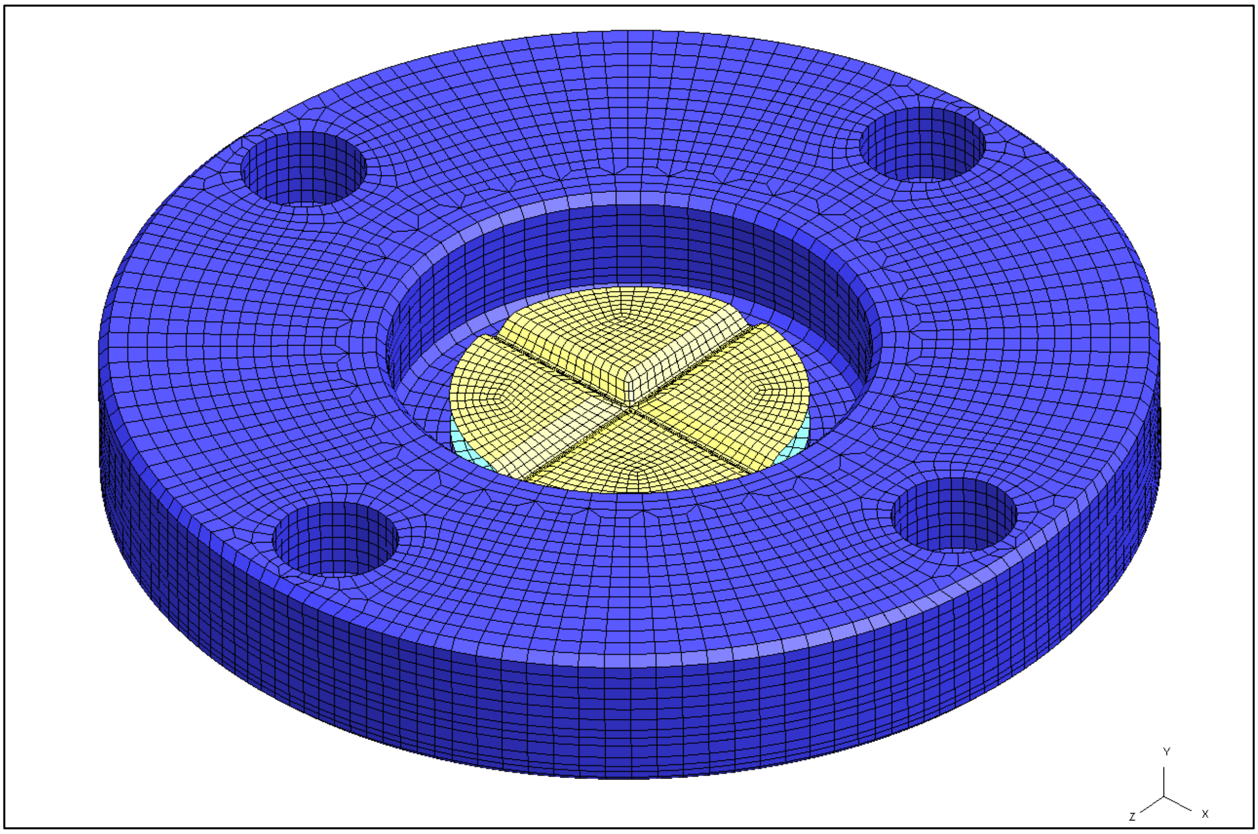

Figure 5 – Finite element model of Lid Filter Assembly

The blast loadings were identical to those in Figure 2. The load was applied by evenly distributing the total force over a specified set of nodes. The total load applied was calculated assuming that the explosion pressure was applied to the exposed portion of the filter mesh.

Since the filter mesh was not modelled, the explosion loading was applied to either the filter housing or the vent cover. These two loading scenarios bound the loading applied to the filter assembly:

i. The load was evenly applied to the inner circumference of the filter housing (i.e. where the filter mesh is connected to the filter housing). This represents the load that would be experienced by the filter housing if the filter mesh were considered to be very stiff.

ii. The load was evenly applied to the bottom ridge of the filter vent cover. This represents the load that would be applied to the vent cover if the filter mesh were to be considered as very flexible (i.e. the filter mesh deflects and contacts the vent cover, transferring the entire explosion load directly onto the vent cover).

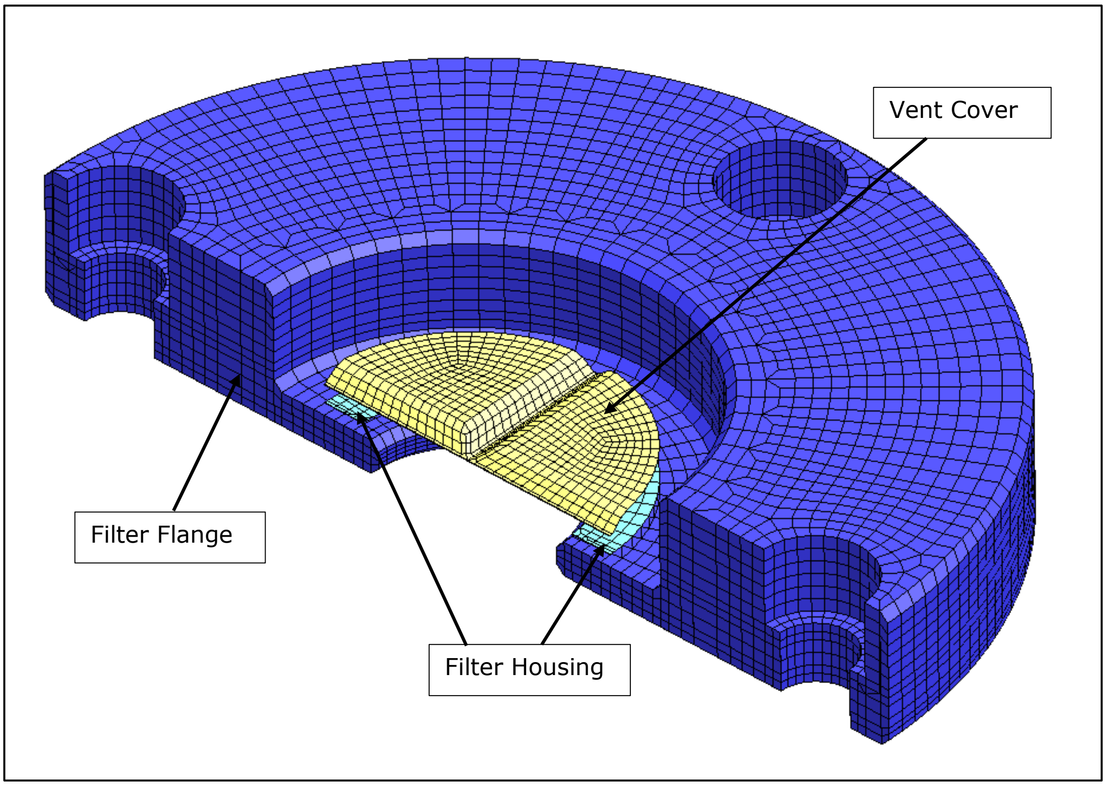

Figure 6 – Section through Finite element model of Lid Filter Assembly

Explosion Loading Applied to Filter Assembly

Four different analyses were carried out, applying either the deflagration or detonation explosion loading to either the filter housing or filter vent cover.

Under the deflagration and detonation explosion loadings applied to the filter housing, there was no plastic strain in the filter flange, housing, vent cover and welds (i.e. the entire filter assembly remained elastic). The maximum von Mises stress observed in the filter assembly was approximately 98 MPa (compared with a yield stress of 175 MPa). Overall, the filter assembly is expected to maintain integrity for the explosion loadings applied to the filter housing.

Under the deflagration and detonation explosion loadings applied to the filter vent cover, there was no plastic strain in the filter flange and housing (i.e. the filter flange and housing remained elastic). The combination of a detonation explosion loading applied to the filter vent cover was found to produce the highest level of damage to the filter assembly. In this case, the filter vent cover experienced plastic strain around the ridges where it is loaded and in the center of the disc with the maximum plastic strain of about 1.7 %, as shown in Figure 7. The welds connecting the filter vent cover to the filter housing experienced up to 8.2 % plastic strain. The material and welds are unlikely to fail since the stainless steel material is very ductile. Overall, the filter assembly is expected to maintain integrity for the explosion loadings applied to the filter vent cover.

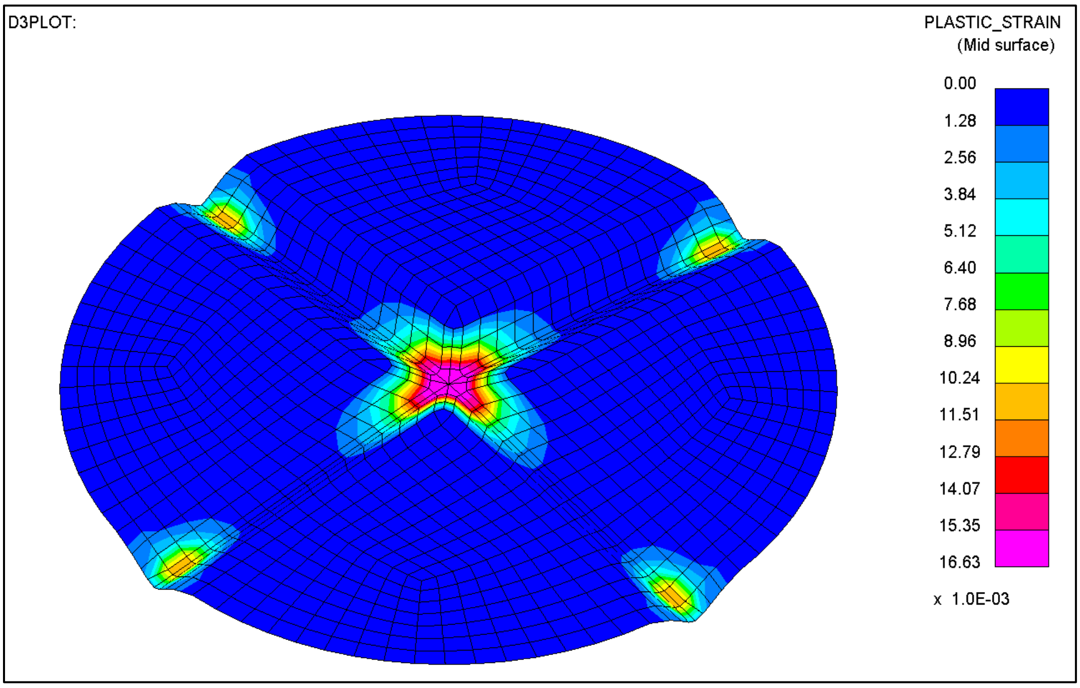

Figure 7 – Plastic strain in filter vent cover after detonation explosion loading

TruVent Filter

In early 2013 Porvair was invited to work with Croft on a filter vent for the Safstore described throughout this paper. Discussions between Porvair and Croft highlighted the need for a filter with a higher rate of particulate retention and high hydrogen diffusivity rating.

The TruVent filter vent originally developed for the WIPP site in Carlsbad New Mexico and designed to meet (and exceeds) the requirements of TRUPACT-II SAR was stipulated as the prime candidate for the Safstore. The TruVent has a filtration efficiency greater than 99.9% (actual HEPA 99.97% @ 0.3μm DOP), an air flow rate greater than 35 ml/min (air) at 1 inch water pressure drop and a hydrogen diffusivity greater than 2.03 Mol/sec/Mol Fraction.

Figure 8 – The ‘TruVent’ filter vent

The Test Programme

Porvair set about conducting a range of tests to further examine the performance criteria of the TruVent. These tests included; a pressure (detonation) resistance test to prove its capability to withstand an 18.6 barg (270 psig) differential/rapid transient, a water retention test and an effect of fluid and humidity test.

Static Pressure Withstand

A representative drum filter of the same diameter, construction and filter media as the TruVent, was loaded into a cylinder containing mineral oil. A hand pump was used to raise the internal pressure of the cylinder to 20 bar and held for 3 minutes. Although the filter media visibly deformed to bear onto the vent cover, as shown in Figure 9, the post test filter performance did not markedly differ from pre test results [2]. The results of the static pressure tests are present in Table 1. The table shows the pressure required to make the representative drum filter pass its first bubble and is measured in inch water gauge (“W.G).

Figure 9 – Filter deformation post 20 bar burst test

Dynamic Pressure Withstand

A secondary test has been undertaken to more accurately simulate a detonation pulse. In this instance a purpose designed rig was set up to deliver a near instantaneous pressure pulse. The same filter type as for the previous test was secured to the rig, and subjected to 20 pressure pulse cycles at 18.6 barg, with each pulse having a duration of 80ms. Following the test the filter media was again shown to deform, but retain its integrity. Pre and post test bubble point measurements (presented in Table 1) recorded an approximate 10% drop in performance due to crushing of the filter media, making bubble penetration more difficult [3].

Table 1- Pressure withstand of a mock TruVent filter pre and post pressure loading tests

Test	Pre Test Withstand Pressure ("W.G)	Post Test Withstand Pressure ("W.G)
Static Pressure Test	58.7	58.8
Dynamic Pressure Test	66.4	73.9

Conclusions

This paper has highlighted throughout the advantages of using a RSC over more traditional waste packages. By providing innovative design features such as a DCI body for more efficient shielding and a greater internal volume for the waste, a double lid arrangement to provide a verifiable containment system and separate shielding and HEPA filter vents to manage gas generation, an RSC such as the Safstore can accelerate decommissioning, provide long term storage and eventual disposal of a wide range of wasteforms.

The case study provided within demonstrates the Safstore's ability to successfully mitigate one of the high risk problems associated with long term storage of ILW; hydrogen generation. By using Porvair HEPA filter vents to passively control the hydrogen volume within the Safstore a hydrogen deflagration/detonation event can be avoided. However from the FEA work presented by Arup we can see that the Safstore and filter vent is expected to withstand such an event.

A global model of the Safstore and a component model of the lid filter assembly have been analysed for two internal hydrogen explosion loading cases, a detonation and a deflagration.

The global model of the Safstore, demonstrates that the stresses in the body and lid were low and with a good margin to the yield stress of the material. The lid bolts remained elastic in the deflagration loading and suffered a very small amount of plastic strain in the detonation loading. Therefore, the integrity of the Safstore will not be compromised by the internal hydrogen explosion.

During the detonation and deflagration explosion loading cases for the component model of the lid filter the loading was applied to the model in two different ways which bounded the response – to the filter housing rim and to the filter vent cover. The combination of a detonation explosion pulse with the loading applied to the filter vent cover was found to produce the highest level of damage, with the welds connecting the filter vent cover to the housing experiencing up to 8.2% plastic strain. This is a relatively small plastic strain and the welds are unlikely to fail. Therefore, the integrity of the lid filter will not be compromised by the internal hydrogen explosion.

Further physical analysis by Porvair on the HEPA filter vent shows that if subject to a 18.6 barg pressure spike the filter's mesh will deform but remain intact and that the filter's flow rate is unaffected. Continued cyclic loading of the filter at 18.6 barg also shows that the filter's performance marginally reduced and it is therefore safe to conclude that following a hydrogen deflagration/detonation the HEPA filter vents would function normally.

Based on the evidence provided it can be concluded that if a Safstore were to suffer a hydrogen deflagration/detonation event, the containment system would remain intact and the HEPA filter vent would continue its passive role of gas management and hydrogen diffusion which would help to avoid a further deflagration/detonation event.

References

1. IAEA Safety Standards, Regulations for the Safe Transport of Radioactive Material, No SSR-6, 2012 Edition.
2. Porvair Filtration Group, Porvair Filtration Test and Development Centre, Burst Test (MN0901124), Memorandum T3835, 18February 2013.
3. Porvair Filtration Test and Development Centre, Detonation Resistance (MN0901124/M099421), Memorandum T3898, 3 April 2013.