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Development of a family of Robust Shielded Containers for the Storage, Transport and Disposal of Intermediate Level Waste

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Abstract

Typically in the UK, Intermediate Level Waste (ILW) is retrieved, sorted and encapsulated in a cement grout within thin walled stainless steel waste containers. Two main approaches to packaging have been employed:

- Unshielded packages, for higher activity ILW which require remote handling and shielded facilities for storage as well as separate shielded containers for transport in the public domain.
- Shielded packages, for lower activity ILW. Due to their integral shielding these designs are capable of being handled using standard industrial equipment and stored in simple stores that allow for controlled man access.

In both cases, performance of the waste package is met by the combination of the wasteform and the container. In contrast, an innovative type of self-shielded container, typically manufactured from ductile cast iron, named Robust Shielded Containers (RSCs), is being pursued by a number of site license companies. RSC's place little or no reliance of its performance on the wasteform and this approach simplifies the waste retrieval and packaging processes which can have significant cost and programme and hazard reduction benefits.

For any waste package one of the most onerous performance requirements is the performance in impact accident conditions, representing drop accident scenarios during interim storage, transport in the public domain and during operations at a Geological Disposal Facility.

This paper summarises the design development by Croft Associates Ltd on its SAFSTORE range of RSCs and presents the work undertaken by Arup for Croft Associates Ltd on the impact performance of the SAFSTOREs, including:

- impact analyses to define the geometric details of the containers;
- material test programme (a) to define the stress strain behaviour of the material at a range of temperatures and at different strain rates, and (b) to define the failure behaviour of the material with strain rate and tri-axiality;
- material level benchmarking to derive material properties suitable for finite element analyses,

to estimate failure and to validate the material model;

- design, manufacture and physical impact testing of a prototype container; and
- pre-test analyses to estimate the behaviour and post-test benchmarking to validate the analysis model.

Introduction

In the 1980s the UK Nuclear Industry Radioactive Waste Executive (NIREX), which is now 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 packages 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 the 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. Compared to what were traditionally called unshielded waste packages stored in heavily shielded buildings, RSCs offer opportunities for storing such wastes in much simpler stores. This offers 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 handling 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.

Figure 1 - Robust Shielded Containers[1]

[1] Croft Associates Ltd products

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 since the wastes may be 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 9 m drop in worst container orientation onto an unyielding surface, a 800 ^{O}C all engulfing fire test and a 0.5 m 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 0.5 m punch test which met a customer's onsite transport requirements.

Figure 2 – Family of Robust Self-Shielded Containers[1]

Drop Impact Finite Element Analyses

As part of the early design development of the Safstore container, preliminary impact analyses using relatively simple finite element models were carried out to examine the performance in the various drop impact scenarios and identify any areas of the design that could be improved. Many drop impact scenarios were assessed including:

- 9 m Base Down onto a flat target.
- 9 m Centre of Gravity (CG) over Lid Long Edge onto a flat target.
- 9 m CG over Lid Short Edge onto a flat target.
- 9 m CG over Lid Corner onto a flat target.
- 9 m CG over Side Edge onto a flat target.
- 9 m Slap Down 5°, 7.5°, 10°, 12.5° and 15° Lid Short Edge onto a flat target.
- 9 m Base onto corner of aggressive target.
- 9 m Flat large side onto a flat target.
- 9 m Flat small side onto a flat target.
- 4.5 m Top Down onto a flat target.

Subsequently, further preliminary impact analyses using more detailed finite element models were carried out to confirm the expected performance in the various drop impact scenarios. The impact performance was considered to be satisfactory, with no failure of the body or lid predicted and no loss of containment. The detailed finite element analyses allowed a deeper understanding of the complex non-linear interactions involved in the impact behaviour, which meant that further design changes could be tested and incorporated into the actual design to improve the impact performance.

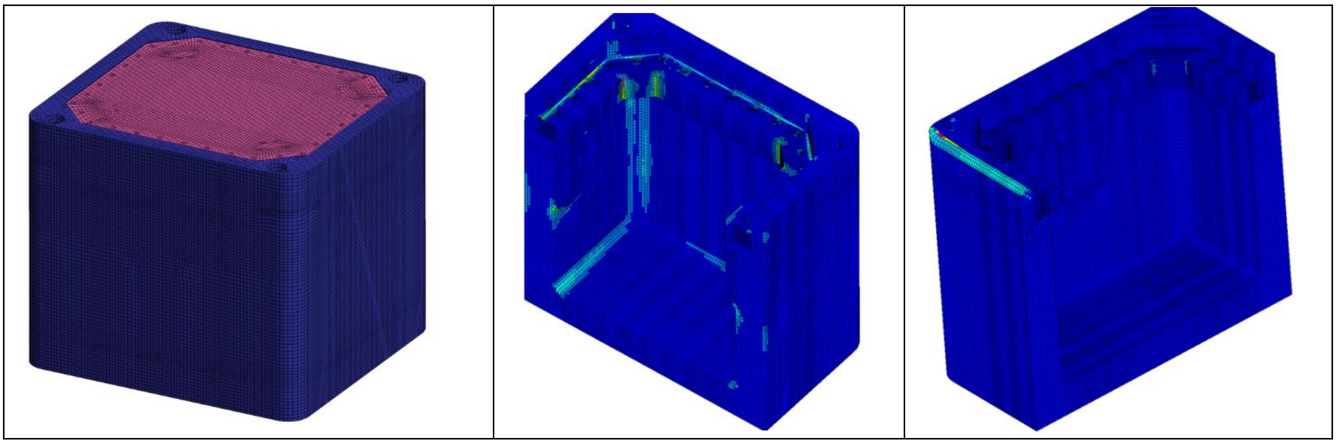

Figure 3 – Examples of finite element model and analysis results

Preliminary Brittle Fracture Assessment

A full brittle fracture assessment would take material data from brittle fracture tests on the DCI, detailed stress data from the impact analyses and the minimum flaw size that could be detected to determine whether a brittle fracture failure mechanism was a possibility under the drop impact loadings. However, at the early stages of the container development, brittle fracture material tests had not yet been carried out on the DCI and the specifications for flaw detection had not yet been produced. Therefore, a preliminary fracture mechanics assessment was undertaken to inform the design and estimate the maximum size of flaw that would be permitted, and would need to be detected, to ensure that brittle fracture would not occur during a drop impact scenario.

This preliminary brittle fracture assessment used the stresses derived from the finite element analyses of the drop impact scenarios, published information on DCI material properties and the principles given in BS 7910 [4] to predict the maximum permitted flaw sizes. The results of this preliminary assessment showed that the expected permissible flaw size was sufficiently large that it would not pose a problem with regards to the specifications for flaw detection and that any cracks that might develop would not compromise the integrity of the container.

Hydrogen generation, venting and explosion loading

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. 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.

The Safstore uses Porvair HEPA filter vents to passively control the hydrogen volume within the Safstore and mitigate hydrogen generation (one of the high risk problems associated with long term storage of ILW), ensuring that the hydrogen concentration is well below the lower flammability limit and giving confidence that the probability of an explosion event is low. Work was carried out to demonstrate the Safstore's ability to successfully mitigate hydrogen generation [2], including:

- Non-linear finite element analyses to show that the Safstore will withstand a hydrogen deflagration/detonation event, with the Safstore expected to remain elastic and the integrity of the Safstore intact after an internal hydrogen explosion.
- Non-linear finite element analyses to show that the filter vent will withstand a hydrogen deflagration/detonation event, with only minor damage to the filter vent structure and the integrity of the filter vent and its fitting intact after an internal hydrogen explosion.
- A range of tests conducted by Porvair on the performance of the TruVent HEPA filter, including a pressure resistance test to prove its capability to withstand the peak differential /rapid transient pressure, a water retention test and an effect of fluid and humidity test.

Figure 4 – Porvair TruVent Hepa filter and finite element model of filter and housing

Full-scale drop test and pre-test and post-test FE analyses

In order to demonstrate the impact performance of the Safstore, a full-scale drop test was to be carried out. Prior to the full-scale drop test, further finite element analysis work was carried out to:

- Model the container contents in the configuration that was to be drop tested.
- Model the deformability of the target that would be used for the drop test.
- Investigate the sensitivity of the impact performance to a range of possible DCI material properties.

Before the drop test, many of the material properties of the components to be used in the drop test (e.g. the target, contents and the DCI container) were not known precisely. Therefore, due to the large number of uncertainties relating to the drop test, these pre-test finite element analyses were used to understand some of the risks associated with the full-scale drop test and the range of likely outcomes.

The full-scale drop test of a 30 tonne Safstore, with a drop height of 9 m in the Lid Long Edge orientation, was carried out at BAM in January 2014. In addition to this drop test, a 0.5 m punch test and 800 ºC 30 minute duration fully engulfing fire accident test were also carried out.

Figure 5 – Pictures from full-scale drop test of Safstore DCI container

After the full-scale drop test, the pre-test finite element analysis predictions were compared with the drop test results. This comparison indicated that the material properties of the target had been under-estimated. Therefore, a post-test evaluation analysis was carried out with modified material properties for the target in order to improve the comparison with the target and DCI container deformation. This post-test evaluation analysis provided a generally improved comparison with the drop test results and the analysis adequately captured the overall deformation modes and impact performance of the Safstore container.

Ductile Cast Iron Material Test Programme and Material Benchmarking

In order to obtain robust finite element simulations to demonstrate the impact performance of the containers, reliable static and dynamic mechanical properties of the DCI material need to be quantified. Therefore, a test programme on the DCI material has been carried out, consisting of a number of tensile tests on DCI test specimens at a range of different strain rates.

The tensile tests were performed at various different strain rates, ranging from 1.8 x 10^{-4}/s up to approximately 280/s. These tests employed two different test rigs and procedures to achieve the range of strain rates required:

- A servo-hydraulic method for strain rates up to 5/s.
- An impact methodology for higher strain rates.

For each tensile test, the full stress-strain curve up to failure of the test specimen was obtained.

Figure 6 – Examples of DCI tensile test specimens

The results from this test programme were assessed and the following conclusions have been drawn:

- The DCI material that was tested meets the minimum specified properties given in BS EN 1563:2011 [3].
- The results from the test programme were very consistent and appear to show good repeatability and reliability.

These test results have been processed and an equation has been derived to represent the true stress vs. true plastic strain curve at different strain rates. This equation has then been used to derive the stress-strain curves for the DCI material to be used in the finite element models.

In addition to the tensile tests carried out on the DCI material, dynamic tensile tests at a range of strain rates were also carried out on the material used for the lid bolts.

The failure characteristics of the DCI material are dependent on the stress tri-axiality. Preliminary material tests to examine the tri-axial failure behaviour of the DCI material have been carried out using notched round bar tensile tests. The results of these preliminary tests have been used to develop an understanding of the allowable strain at different stress tri-axialities. Further tests on the DCI material are to be carried out to examine the material failure characteristics across a wider range of stress tri-axialities.

Conclusions

This paper has highlighted the advantages of using a Robust Shielded Container over more traditional waste packages. By providing innovative design features such as a Ductile Cast Iron 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, a RSC, such as the Safstore, can accelerate decommissioning, provide long term storage and eventual disposal of a wide range of wasteforms.

Through a combination of detailed finite element analyses, full-scale drop tests and material testing, the impact performance of the Safstore has been demonstrated. In addition, a combination of laboratory testing and finite element analyses has demonstrated the Safstore's ability to successfully mitigate the risks of hydrogen generation and the potential for hydrogen explosions by using Porvair's TruVent HEPA filter.

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