THE STRUCTURAL INTEGRITY OF HIGH LEVEL WASTE CONTAINERS FOR DEEP DISPOSAL

T. J. Keer, Ove Arup & Partners, London, UK
N. J. Martindale, Ove Arup & Partners, London, UK
B. Haijtink, Commission of the European Communities, Brussels, Belgium

ABSTRACT

Most countries with a nuclear power program are developing plans to dispose of high level waste in deep geological repositories. These facilities are typically in the range 500-1000m below ground. Although long term safety analyses mainly rely on the isolation function of the geological barrier, for the medium term (between 500 and 1000 years) a barrier such as a container (overpack) may play an important role. This paper addresses the mechanical/structural behaviour of these structures under extreme geological pressures.

The work described in the paper was conducted within the COMPAS project (Container Mechanical Performance Assessment) funded by the Commission of the European Communities and the United Kingdom Department of the Environment. The work was aimed at predicting the modes of failure and failure pressures which characterise the heavy, thick walled mild steel containers which might be considered for the disposal of vitrified waste. The work involved a considerable amount of analytical work, using 3-D non-linear finite element techniques, coupled with a large parallel program of experimental work. The experimental work consisted of a number of scale model tests in which the response of the containers was examined under external pressures as high as 120MPa. Extensive strain-gauge instrumentation was used to record the behaviour of the models as they were driven to collapse.

A number of comparative computer calculations were carried out by organisations from various European countries, in order to evaluate the capability of various different non-linear programs. These organisations were Ove Arup & Partners (UK, project managers), SCK/CEN (B), NAGRA (CH), Paul Scherrer Institute (CH), STEAG Kernenergie GmbH (D), Equipos Nucleares S.A. (E) and CEA (F). Programs used included OASYS DYNA3D, ADINA, COSMOS, ANSYS, CASTEM and SYSTUS. Correlations were established between experimental and analytical data and guidelines regarding the choice of suitable software were established.

The work concluded with a full 3-D simulation of the behavior of a container under long-term disposal conditions. In this analysis, non-linearities due to geological effects and material/geometry effects in the container were properly accounted for.

INTRODUCTION

Deep Disposal of High Level Waste

Within much of Europe, High Level Waste (HLW) is produced when spent nuclear fuel is reprocessed to recover uranium and plutonium. The radioactivity in the resulting liquid is immobilised by vitrification (dispersion in a glass matrix).

Emplacement in stable geological formations is generally considered to be the most effective way of isolating the vitrified HLW until its radioactivity decays below levels which pose an unacceptable risk to man and the environment. Many disposal schemes involve the overpacking of the vitrified HLW canister before disposal.

HLW Overpack Designs

Previous research has developed a number of preliminary designs for HLW overpacks. Two distinct container concepts have emerged - see Fig. 1. The first is a corrosion-resistant container, typically a supported shell of titanium alloy which derives its strength from a solid filler between canister and overpack. The second concept design is a stressed shell container, typically a thick-walled mild steel container with increased wall thickness to allow for corrosion during extended burial.

The various overpack designs proposed had considered different geological conditions and corrosion philosophies. However very little was known about the failure modes and strengths of these containers when subjected to external pressures representative of deep geological disposal conditions. Previous experimental work performed by AECL at Whiteshell had focused on a thin-walled container for the direct disposal of spent fuel (1). CEA at Saclay had tested vitrified HLW canister heads at pressures of up to 28MPa (2).

COMPAS (Container Mechanical Performance Assessment)

The COMPAS Project was set up in 1987 with the aim of developing analytical techniques to the point where the mechanical behaviour of HLW overpacks could be accurately predicted. A major program of testwork was commissioned culminating in pressure tests on scale models of thick

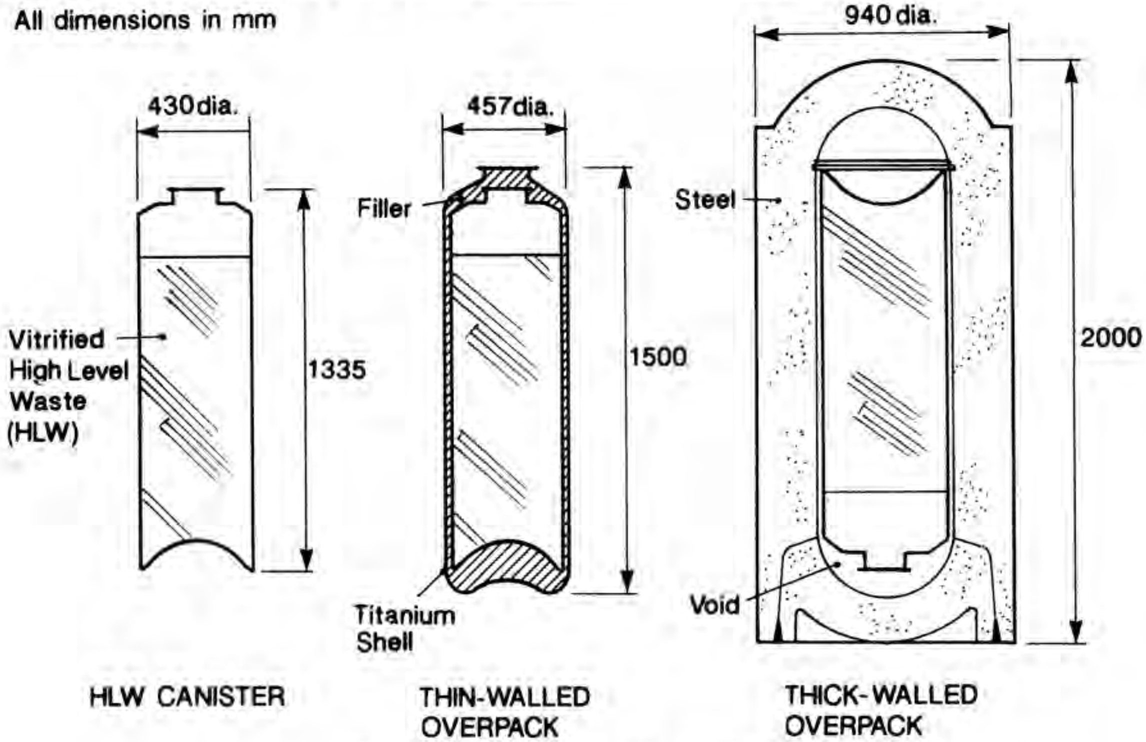


Fig. 1. HLW Canister and Overpacks.

walled HLW overpacks. The results from the experimental work were used to validate the analytical capability developed. This paper describes the program of work performed by Ove Arup & Partners in the COMPAS Project, which was funded by the Commission of the European Communities and the United Kingdom Department of the Environment. Representatives of organisations from several European countries monitored the progress of the project and contributed to the analytical work - SCK/CEN (B), NAGRA (CH), Paul Scherrer Institute (CH), STEAG Kernenergie GmbH (D), Equipos Nucleares S.A. (E) and CEA (F).

PREPARATORY STUDIES

The main objective of COMPAS was to demonstrate the ability to predict accurately the behaviour of a HLW overpack under external pressure. The work culminated in extensive and expensive pressure tests but some of the preparatory work is also of relevance to the design and analysis of overpacks. The three most important activities (chosen to provide useful information without the costly testwork of later phases) comprised a directory of computer codes suitable for the analysis of HLW overpacks, an identification of likely disposal scenarios, and the execution of a series of simply defined analytical benchmarks.

Directory of Codes

Twelve computer codes, considered suitable for the stress analysis of HLW containers, were identified. The list was not exhaustive but included all codes used by the project partners and some other commercially available and widely used codes. Each program was assessed on a series of criteria (Technical performance, pre- and post-processing facilities, ease of use and running costs) and although no attempt was made to rank the codes in order, several strengths and weaknesses were identified (3).

Identification of Likely Disposal Scenarios

Previous studies had identified the geological formations which are suitable for HLW repositories - clays, granites and salts. Although these media are chosen for specific properties which they share (low permeability, long term stability and high sorption capability of radionuclides) their mechanical properties (e.g. strength and stiffness) differ greatly. As the COMPAS project was not concerned with any one particular disposal medium, but rather with increasing the knowledge about all media, all three disposal formations were considered.

The aim of this activity was to determine the maximum loads acting on a container during the duration of its burial. Knowledge of these loads was necessary for the specification of test facility requirements and the calculation of real container behaviour to be performed later. Information was gathered from the project partners and previous research studies and two "worst" loadcases were identified:

(i) a uniform external pressure of up to 90MPa, envisaged of burial in salt at depths of up to 2500m.

(ii) an anisotropic (non-uniform) pressure, most likely to occur in granite.

Leakage of water through the borehole casing could give rise to backfill swelling exerting pressures around the sides of the container before the ends, or non-uniform thickness of backfill material surrounding the container could lead to anisotropic pressures as a result of swelling.

These loadcases were considered to be pessimistic but nevertheless feasible.

First Benchmark

A preliminary benchmark exercise was performed to increase knowledge of the ability of the chosen finite element codes and to identify potential problems likely to occur with the more complicated analyses to follow. Although the problems specified were chosen for their simple definition (transverse squashing of thick-walled rings) nonlinearities (material and geometric) ensured the analytical problems were non-trivial. A series of compression tests on mild steel rings produced data to allow direct comparison - see Fig. 2. The exercise demonstrated the ability to produce results to within acceptable limits of accuracy (Fig. 3 shows a typical comparison of results) but there were indications that some codes would not be able to cope with a significantly more complex three-dimensional analysis. The report on this work has been published by the Commission of the European Communities (4).

Fig. 2. Preliminary Testwork-Ring Compression Test.

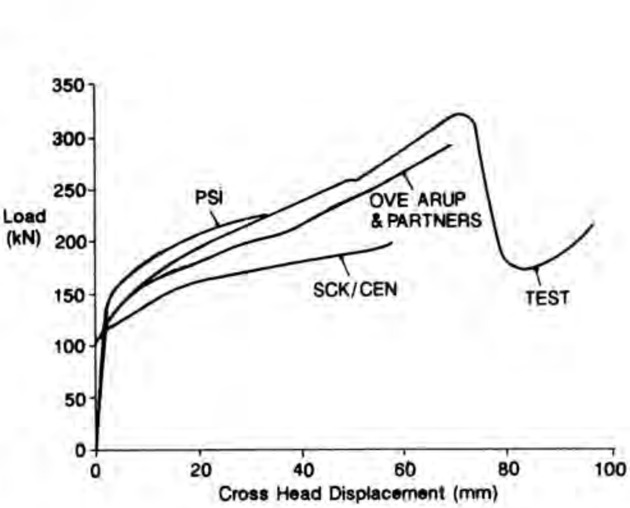


Fig. 3. Ring Tests-Comparison of Results.

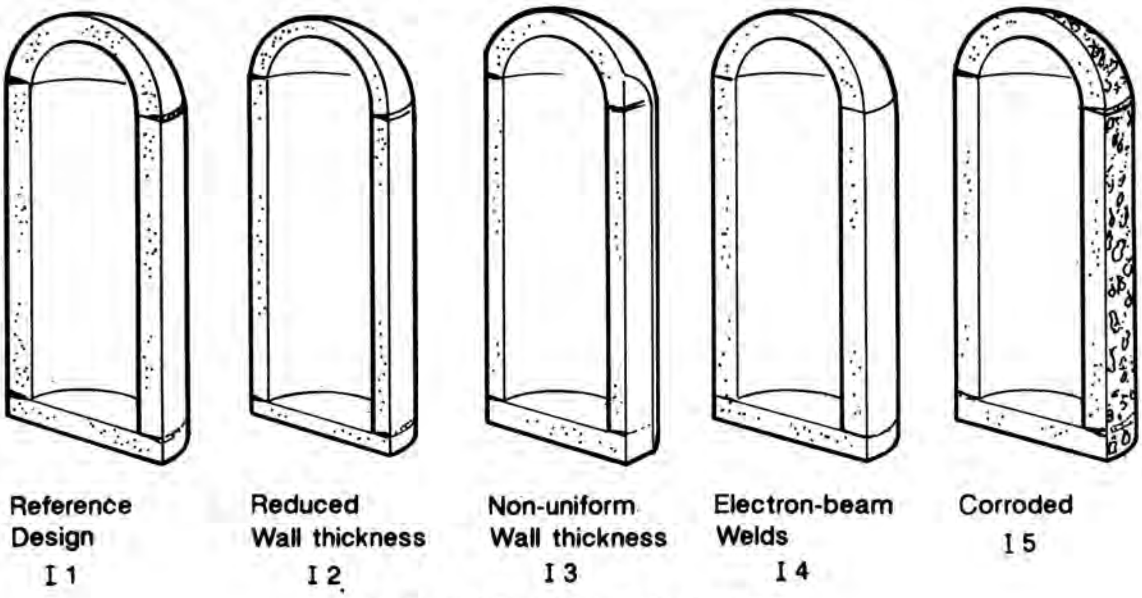
COMBINED PROGRAM OF CONTAINER TESTWORK AND ANALYSIS

High level waste overpacks must be designed to withstand high pressure (not necessarily uniform) over long periods of time. The ability to accurately analyse and predict container behaviour is attractive as some proposed loadcases may not be applied in a test environment and, where testwork is feasible, it is often expensive and time consuming. Although the physical testing of new designs will always remain an important part of the design program, the ability to repeat computational analyses quickly and with confidence is an attractive goal which this phase of the work addressed.

While the development of an analytical capability was one objective of this study, increased information about the likely behaviour of real containers was also sought. With these aims in mind, a two-stage program of container testing was commissioned. The containers and the loading imposed on them were as accurate as possible but restrictions were placed on test-piece size (one third scale) and strength (failure pressure < 140MPa) by the limited size and pressure rating of the test facility available. These restrictions did not compromise in any way the validity of the tests.

Container Design

Two series of one third scale containers were designed, manufactured and tested. These were referred to as the Intermediate and Advanced container families. The designs were similar but the philosophy for each phase was differ-



Reference Design I 1

Reduced Wall thickness I 2

Non-uniform Wall thickness I 3

Electron-beam Welds I 4

Corroded I 5

Fig. 4. Intermediate Testwork Containers.

ent. All models were manufactured from mild steel, the material proposed for most thick-walled HLW overpacks.

The Intermediate Testwork containers were not meant to be accurate representatives of any existing HLW overpack design. Instead the opportunity was taken to investigate the effect of varying different design parameters with a view to gaining insight into the more important features to be considered during the design of these types of containers - see Fig. 4. The limited maximum pressure offered by the test facility meant that the reference container was substantially thinner than existing designs, which include an increase in wall thickness to allow for corrosion during extended burial. These test-pieces therefore represented containers towards the end of their burial period. The effects of reduced wall thickness, cross section irregularity, non-uniform corrosion (Fig. 5) and welding methods were all investigated. No attempt was made to model the vitrified waste inside the containers. Seven containers in total were tested.

Fig. 5. Detail of Corroded Container I5.

For the Advanced Testwork, emphasis shifted away from an investigative program towards assessing the likely performance of a real HLW overpack. The experience acquired previously was used to design a now quite accurate scale model of a HLW overpack (Fig. 6). This reference design was used as a basis for the other containers in the family, but was not tested as it was believed to have a collapse pressure greater than that available at the test facilities. During the identification of likely disposal scenarios, it had been suggested that a buried container might be subjected to an anisotropic pressure distribution due to non-uniform swelling of the backfill. Although the test facility used could only apply an isotropic pressure to the external surface of the test-pieces, the asymmetry problem was of interest to all the partners as it gave a sterner test of their analytical capabilities. For this reason two of the containers were pre-deformed to have an elliptical cross-section at their mid-height. One of these containers was manufactured with a spark-eroded crack in a region of tensile stress. It was hoped that this container would confirm the belief that fracture would not contribute significantly to container failure, and would also provide information against which to benchmark fracture mechanics finite element techniques. A third container had slightly reduced wall thickness. For all containers attention was paid to using the same material, end closure details and weld methods as

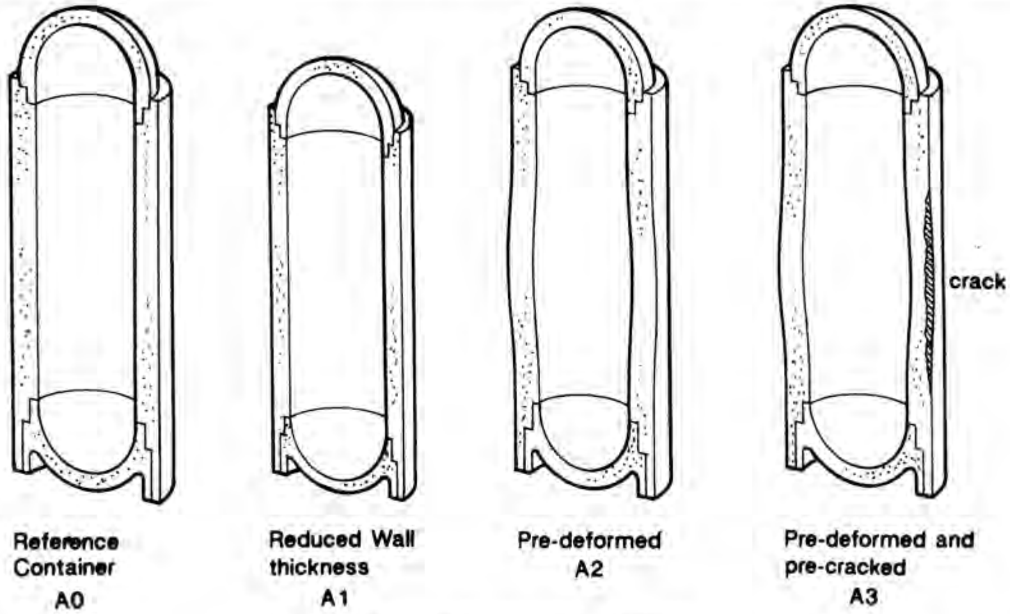


Fig. 6. Advanced Testwork Containers.

would be used in practice. Figure 6 compares the four containers designed for the Advanced Testwork program.

Test Procedure

For both Intermediate and Advanced testwork programs, the containers were tested one at a time in a test well at the Schlumberger test facility in Paris. The containers were subjected to an isotropic external pressure. The pressurising medium was water.

Figure 7 shows the physical arrangement of the tests. The containers were extensively strain-gauged (high elongation, ±10%, gauges) during testing to provide as much information as possible about their behaviour up to and including failure. The output from the strain gauges was subsequently used to assess the accuracy of the computer analysis predictions. Two pressure transducers and two temperature sensors provided additional data. During testing the container was enclosed in a cylindrical rubber jacket, filled with oil to provide electrical insulation. A purpose built well head incorporating a 98 pin adaptor was used to connect the instrumentation to recording equipment outside the test well. All channels of strain, pressure and temperature data were recorded directly onto microcomputer floppy discs for portability and easy post-processing of results.

The test procedure followed was identical for all containers. Three containers of the reference Intermediate design were tested first in order to demonstrate the repeatability of results and check the accuracy of the instrumentation. Thereafter a single container of each type was tested. Prior to each test, the correct operation of the strain gauges was confirmed by raising and lowering the pressure within the elastic range of the material. The test involved increasing the pressure from atmospheric, initially in steps of 5MPa, then in steps of 1MPa as the material yield point was approached. Strain gauge data was recorded after each step in pressure. The time interval between recording successive sets of data was approximately 45 seconds. The pressure was increased up to the point at which the container failed,

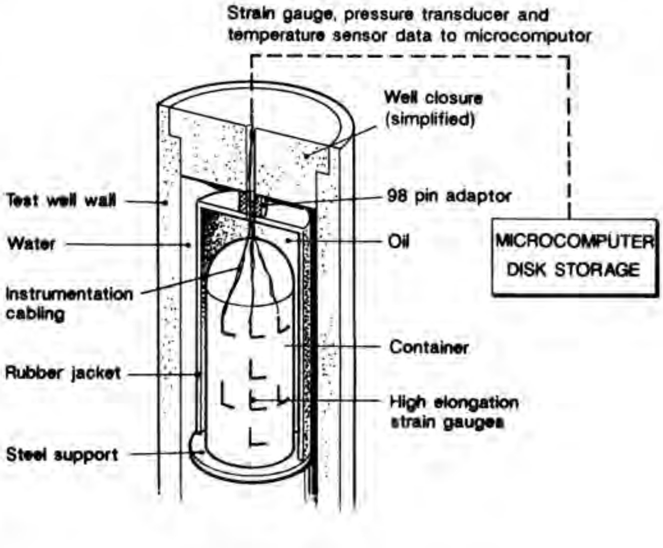


Fig. 7. Test Arrangement.

indicated by an audible 'bang', and a sudden decrease in the well pressure. The pressure was then allowed to return to atmospheric, and the container removed and examined to determine the mode of failure. The failure pressure could be determined to within (-0, +1MPa) of the value of pressure at the last set of readings recorded. These values of failure pressure were subsequently found to correspond to the sharp changes in strain data which would be expected at the onset of buckling.

Test Results

Seven Intermediate containers and three Advanced containers were successfully tested. While details of each container's behaviour are available (5, 6), a more general summary is given here.

All containers failed by buckling of the mid-height region of the cylindrical body. Figure 8 shows container I3 (Intermediate testwork, non-uniform wall thickness) after testing. To prevent damage to the test well in the event of container rupture and rapid pressure loss, each test-piece contained a loose-fitting aluminium cylinder which was smaller than the vitrified HLW canister which a real overpack would enclose. The buckling of the containers was therefore halted before 'complete' collapse occurred. No tensile failure of the mild steel was observed and all welds remained intact.

Fig. 8. Post Test Container I3.

The main conclusions from the Intermediate phase of testing (investigating the relative importance of different design parameters) were:

i. The three tests on identical containers demonstrated repeatability and gave confidence in the test procedure.

ii. Each container was observed to undergo symmetric plastic deformation before buckling.

iii. The weld methods used (TIG and Electron Beam) had only a small effect on container performance.

iv. The test on the corroded container suggested that the reduction in failure pressure (approximately 15% below the reference container) due to the simulated corrosion was nearer to the average reduction in wall thickness (approximately 5%) than the maximum reduction (approximately 50%). Localised corrosion will not therefore necessarily greatly impair the container's ability to withstand load.

The main conclusions drawn from the Advanced Testwork were:

v. All significant deformation occurred in the mid-height region of the container body. There was little distortion of the lid or base and there was no evidence of weakness at the welded interfaces.

vi. Fracture was not the cause of failure of the precracked container. Gross plastic deformation dominated.

vii. A typical HLW overpack can withstand very high pressures. This theme is followed in greater detail later.

Verification of Analytical Techniques

The physical testwork provided increased insight into the behaviour of a typical HLW overpack, but the main objective of the COMPAS Project was to demonstrate that finite element analysis techniques could be used to accurately model the container tests. Where there is confidence in analysis methods, they may be used to investigate variations which might otherwise not be considered, and even disposal scenarios which may not be reasonably repeated in the laboratory (e.g. non-isotropic pressure loads).

It was decided that the best way to assess the accuracy of the analyses was by comparing the partners' predictions of (i) failure pressure and (ii) strain v pressure curves (at selected points on the surface of the containers) with the test results. This comparison method proved to be straightforward and useful.

Table I compares the failure (collapse) pressures for the three Advanced Testwork containers with the analytical predictions. For container A1 (axisymmetric, reduced wall thickness) the calculations are generally accurate. For containers A2 and A3 (pre-deformed) the calculations are not all so accurate but, where not correct, are conservative.

TABLE I
Advanced Container Tests-
Testwork/Analysis Comparison

	A1	A2	A3
Test failure pressure	65 MPa	110 MPa	105 MPa
Prediction-CEA	65 MPa	85 MPa	54 MPa
Prediction-ENSA	59 MPa	82 MPa	78 MPa
Prediction-Ove Arup	67 MPa	108 MPa	107 MPa
Prediction-PSI	68 mPa	96 MPa	96 MPa

A typical set of strain v pressure curves is shown in Fig. 9. This particular graph compares the major axis circumferential strain for the pre-deformed Advanced container A2. It can be seen that there is considerable spread between analytical predictions, and this corresponds to the varied accuracy of the calculations. It should be noted that this is just one of many such comparisons, and the accuracy of these curves does not necessarily imply that any particular partners' other calculations were equally accurate/inaccurate.

These analyses are described in detail in reports on the two phases of testwork published by the Commission of the European Communities (5, 6). The specific conclusions about the analytical methods used which were drawn from this exercise are:

i. A careful choice of material model is needed. Simplifying the material definition (e.g. by assuming a constant Hardening Modulus) can lead to inaccurate results.

ii. As buckling was the mode of failure of all containers (even when an axisymmetric container was loaded uniformly), this phenomenon must be considered by the finite element package used.

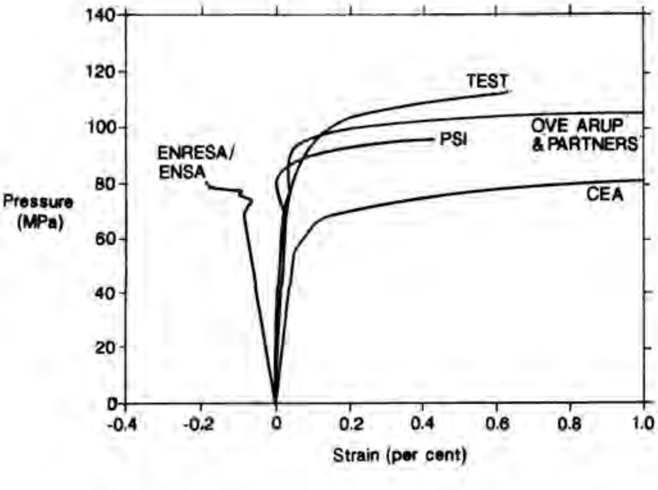


Fig. 9. Advanced Container A2-Comparison of Results.

ANALYSIS OF CONTAINER BEHAVIOR UNDER REALISTIC DISPOSAL CONDITIONS

In the final stage of the project, the analysis of a realistic design HLW overpack was performed to predict its behaviour when subjected to likely repository loads. The analysis work was undertaken with the benefit of experience gained in previous phases of the project when the ability of Ove Arup & Partners to accurately predict overpack behaviour had been demonstrated.

Burial in clay, granite and salt environments was considered and two distinct loading arrangements were identified to encompass all conditions that could be imposed by these media. The aim was to demonstrate the ability of the containers to withstand loads in excess of those that could conceivably arise under repository conditions.

This work used the same analytical methods as had been used for the previous stages of analysis. The container geometry was taken to be that of the Advanced Testwork reference container (not tested because of its high strength) and the two loadcases (one isotropic, one anisotropic) were as defined in the preparatory study of disposal scenarios described earlier. The combination of geometry and load is considered pessimistic (the corrosion allowance increase in wall thickness is removed and the loads are extreme) but not necessarily conservative.

For the isotropic 90MPa pressure, the maximum von Mises stress in the overpack wall was slightly above the yield point, but container integrity was not lost, and indeed further calculations suggested that failure would not occur below a pressure of 200MPa.

Similarly for the anisotropic loadcase (with external pressure varying from 45MPa to 90MPa) the container yielded but was well within its ultimate capacity.

These analyses of a real container in real disposal conditions agreed with the expectations based on experience acquired during previous phases of the COMPAS project. The structural/mechanical integrity of the particular overpack was clearly demonstrated.

CONCLUSIONS

A comprehensive test program has brought increased insight into the structural behaviour of containers used as additional engineered barriers for the deep geological disposal of vitrified high level waste canisters.

The experimental results have been used to validate analytical techniques and there is now confidence in the ability to analyse large three-dimensional models of buried containers.

Although this project concentrated on a representative design of an overpack for vitrified High Level Waste, the analytical techniques developed may be extended to other disposal concepts (e.g. the direct disposal of spent fuel) or new loading scenarios which may need to be considered in the future.

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