Effects of Physical Demands on a Radwaste Canister

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ABSTRACT

Current plans in Spain call for spent fuel and high-level wastes to be stored in a deep geological repository, once they are encapsulated in canisters. Financed by ENRESA (Spanish national company in charge of radioactive waste), a multi-year effort has been dedicated to the study of such canisters under the different physical demands that they may undergo, whether in operating or accident conditions.

The physical demands of interest include mechanical demands, both static and dynamic, and thermal demands. The complete life of the canister has been considered in this project, from the time when it is empty and without lid to the final conditions expected in the repository.

Thermal analyses of canisters have been carried out in three dimensions, in order to evaluate peak temperatures in the spent fuel, thermal stresses in the canister and the volume of bentonite where chemical stability may be threatened by excessive temperatures.

The static loads expected are essentially pressures exerted during storage. Analyses have been carried out with bare canisters as well as with canisters interacting with the guide-tube. Uniform and non-uniform pressures were also considered in the project, although only the former will be described here. Attention is given both to the potential buckling of the canister and to the more gradual process of plastic deformation.

In respect of the dynamic demands, based on the consideration of the life cycle of the canister, a study was first conducted of all credible accidents. Dynamic analyses were then carried out for the various postulated accidents: lid drops onto the canister with different attitudes, fall of the canister onto a punch, tip-over of the canister on a rigid plane and falls of the canister inside the overpack.

All studies were repeated for a number of canister thicknesses in order to determine the sensitivity of the results to changes in this major parameter. Such calculations are useful for the initial design and also guide the expectations for the future, when chemical deterioration will decrease the useful thickness of a stored canister.

INTRODUCTION

The current plan in Spain with respect to spent nuclear fuel is to place it in canisters and to dispose of it in a deep geological repository. The present paper studies the physical behaviour of the type of canisters considered when they are subjected to a number of demands, both accidental an operational; the former obviously tend to be more severe than the latter.

The work summarized here has been carried out in the context of a series of contracts awarded by ENRESA (Spanish national company in charge of radioactive waste) to the Department of Materials Engineering of the Madrid School of Mines. A very complete summary of the research conducted has been edited by ENRESA as one of their technical publications[1], where interested readers can obtain additional information beyond that contained in the present paper. Also, more detailed accounts of specific parts of this research can be found in two PhD theses written[2,3], as well as a number of MSc theses and reports prepared for ENRESA.

DESCRIPTION OF THE CANISTERS

The canisters will have a cylindrical shape, with flat ends, made of hot-rolled carbon steel. The lid will be welded to the body of the canister, thus ensuring the isolation of the contents while maintaining a smooth outer surface.

The materials science aspects of this research were carried out by INASMET. A good account of their findings can be consulted in Smailos et at[4]. No attention will be dedicated here to this part of the research, but the parameters used for describing the material behaviour are representative of the insight gained in such studies.

The material of the canister has been assumed to behave as an elastoplastic solid. The elastic behaviour is characterized by a Young´s modulus of 210 GPa and a Poisson´s ratio of 0.29. The yield stress was taken as 320 MPa, after which the material hardens linearly up to an ultimate stress of 620 MPa, which is attained for a true strain of 0.2. The thermal conduction coefficient is 60 W/mK and the specific heat is 403 J/kgK.

The internal dimensions of the canister, governed by fuel element size, are a diameter of 700 mm and a length of 4300 mm. Thickness is one of the parameters to be optimized, but starting approximations suggest 100 mm for the cylindrical wall and a thickness 20% greater for the base and lid (Fig. 1). The study of different thicknesses is of interest not just as support for the initial design, but also because there will be a gradual loss of structurally useful material by the chemical deterioration expected to occur with time in the repository.

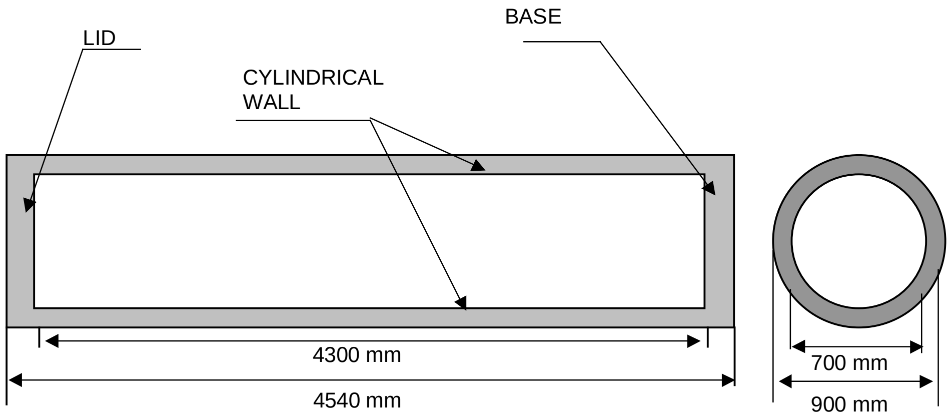

Fig. 1 General dimensions of the canister

Both empty and full canisters have been studied. The latter contain four PWR fuel elements and a granular glass fill in an inert atmosphere. The specific characteristics of the granular fill are still to be defined in detail.

The canisters will be placed along horizontal galleries at 500 m depth. They will be positioned along the central axis of the circular section of the gallery, inside a guide tube. The space left between the guide tube and the host formation will be occupied with a bentonite backfill. The details of the conept of the repository are described by AGP – Ingeniería de Proyecto[5].

THERMAL DEMANDS

The thermal studies were directed to determine the expected temperatures at various points of the canister during the first 30 years in the repository. Specially significant were temperatures in the fuel region (which influence its degradation), peak temperatures and temperature gradients in the canister (related to thermally induced stresses) and temperatures in the bentonite fill (its stability being less reliable beyond 100°C).

It is assumed that the fuel will be cooled for 47 years prior to placing it in the canister. Thus, over the next 30 years, the heat generation expected is that shown in Table 1.

Time after Storage (years)	Power per Element (W)
0	300
1	296
3	287
8	266
13	247
18	230
23	215
30	201

Table 1 Heat generation

Although the analyses reported here are all three-dimensional, both plane strain and axially symmetric analyses were also carried out in order to determine their respective ranges of applicablility in time and in space.

The geothermal gradient has little effect on the results, since it does not influence the dissipation of heat from the canister. At this depth, the natural temperature is taken to be 30°C. Constant properties have been used for the bentonite over the 30 year period, but a range of heat conduction coefficients was considered for the glass fill, from 0.25 to 1 W/mK.

ABAQUS/Standard[6] was used for the thermal calculations. The various symmetries (between parallel galleries, adjacent canisters, etc.) were used to reduce the size of the domain being modelled. Fig. 2 shows the mesh representing everything except for the host formation, which has been removed from this figure for clarity of the more essential regions of the model.

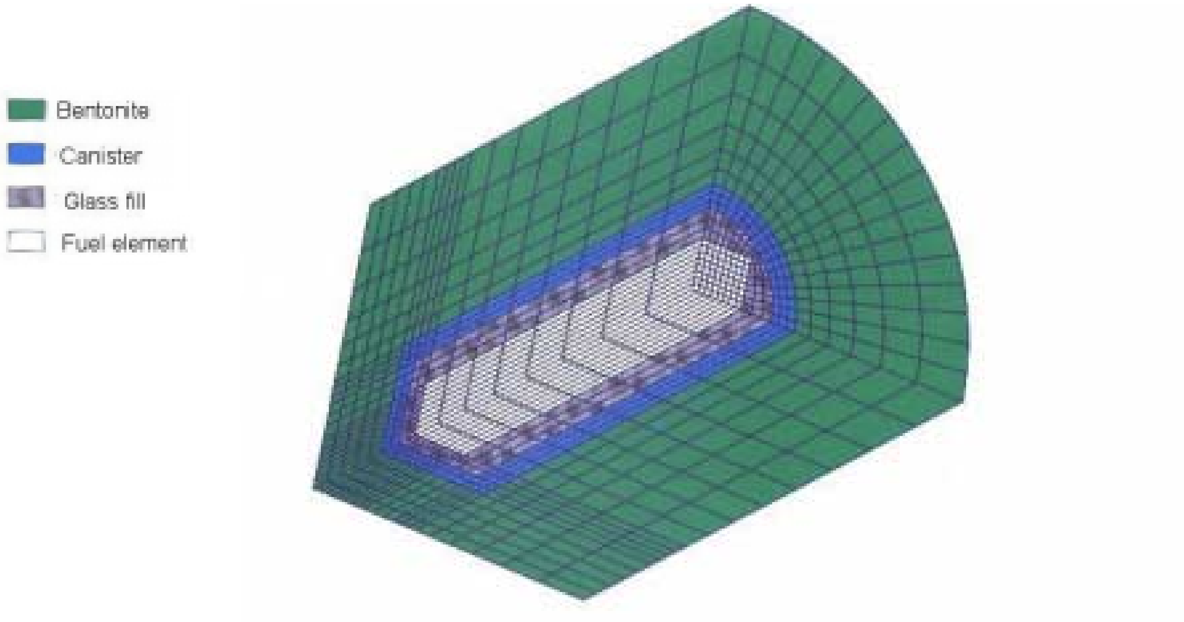

Fig. 2 Mesh with host formation removed

With the higher conductivity for the glass fill, peak temperatures in the fuel are 142°C and occur after about 4 years; this temperature increases to 186°C with the lower conductivity value. In the bentonite, peak temperatures occur after 11 years and reach 107°C in both cases.

Because of possible problems of chemical stability and volume change, it is of interest to determine the region where the bentonite exceeds 100°C (Fig. 3). The thickness of this region is about 6 cm around the central part of the cylinder and 2 cm near the centre of the flat ends of the canister.

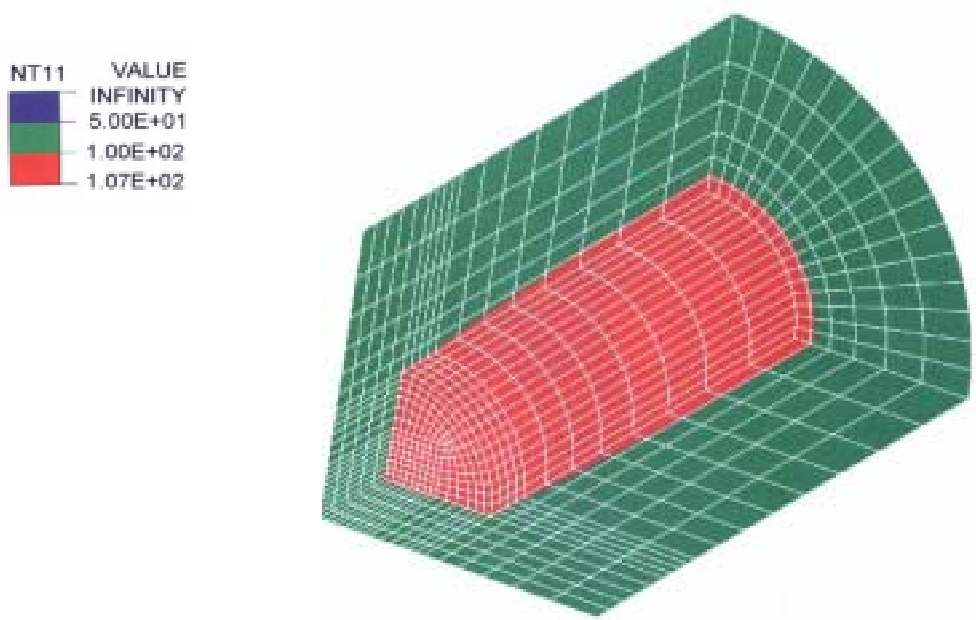

Fig. 3 Region of bentonite exceeding 100°

Thermal jumps across the canister wall are smaller than 1°C and their contribution to the stress field is therefore considered to be insignificant.

STATIC DEMANDS

A large number of combinations of static demands on the canister has been studied, although only a small selection can be presented here. The static loads are mainly the result of external pressures being developed in the repository. Although non-uniform pressures have also been studied, in particular the configurations proposed by SKB[7], we will concentrate here on the cases of uniform pressures leading to plastic yielding or elastic buckling of the canister.

Elastic Buckling

A mesh spanning one half of an empty canister was used for analysing this instability, once again using ABAQUS/Standard. The buckling modes suppressed by the assumed symmetry are essentially torsional modes which are of no interest here. The calculations were repeated with five different wall thicknesses, comprised between 30 and 120 mm for the cylindrical part, maintaining an additional 20% thickness for the base and the lid.

Over the ranges of interest, the shapes of the first two buckling modes (the first one appears in Fig. 4) are not affected by the wall thickness, although the corresponding critical loads obviously are. With a wall thickness of 100 mm, the critical pressures for the first two modes are 0.83 and 1.01 GPa, respectively. The dependence of the critical pressures on thickness appears in Fig. 5. As can be noticed, over the range of thicknesses considered, the critical pressure required for developing the first buckling mode approximately increases with the 2.6 power of the thickness.

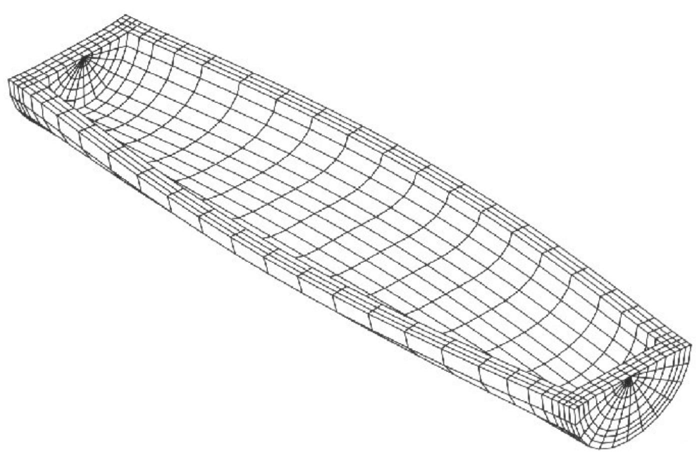

Fig. 4 First buckling mode

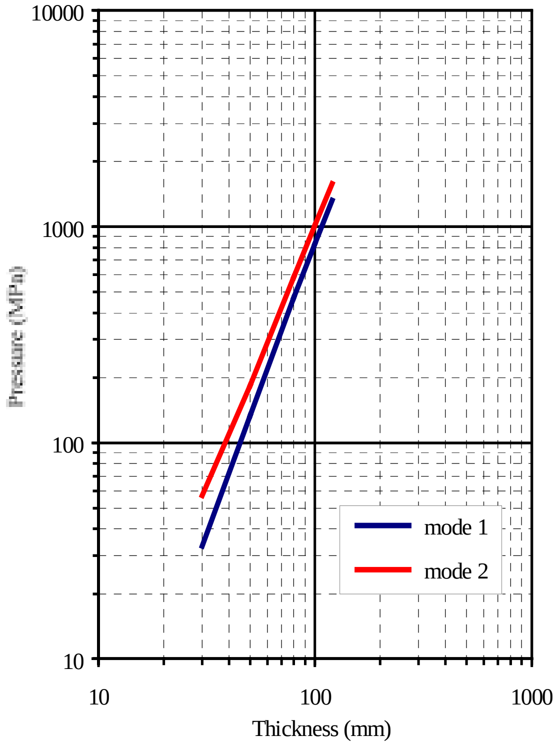

Fig. 5 Critical buckling pressure

Plastic Collapse

An axially symmetric mesh spanning half a canister was used to model the elastoplastic response of the canister under an externally applied pressure. Again ABAQUS/Standard was employed for the calculations. As before, five different wall thickness were analysed, ranging between 30 and 120 mm.

Apart from the local concentration at the base-wall corner, the peak plastic strains do not occur consistently in the same location. Fig. 6 depicts the plastic strains in a canister with 120 mm walls; in this case, the peak values occur at the cylindrical walls. However, for canisters with wall thickness below 100 mm, the maximum strains occur instead in the base and lid of the canister.

Once plastification starts, small increments of the external pressure produce considerable additional yielding in spite of the hardening of the material. Fig. 7 shows the external pressures required for developing peak plastic strains of 2% and 10% as a function of the wall thickness. It is clear that the pressure increment required to progress from 2% to 10% strains is very small; also, in spite of the differences in location of the more highly strained areas, an approximate power law relationship (with 1.7 as the exponent) is again maintained between the wall thickness and the pressure needed to induce a given peak strain.

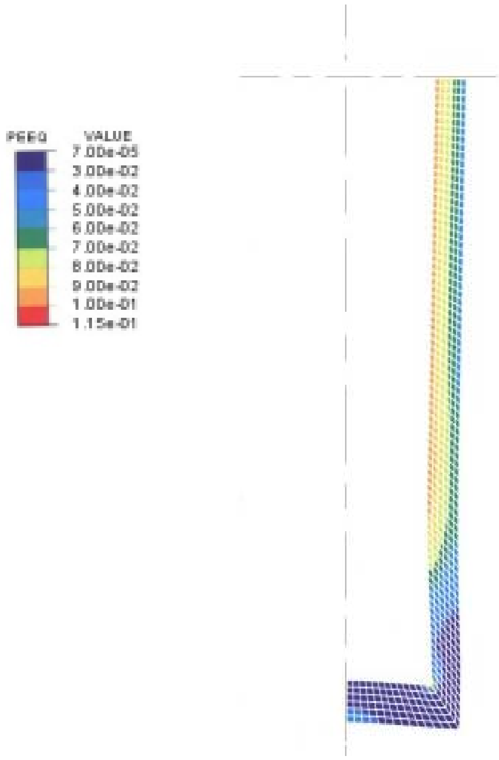

Fig. 6 Plastic strains with 120 mm wall

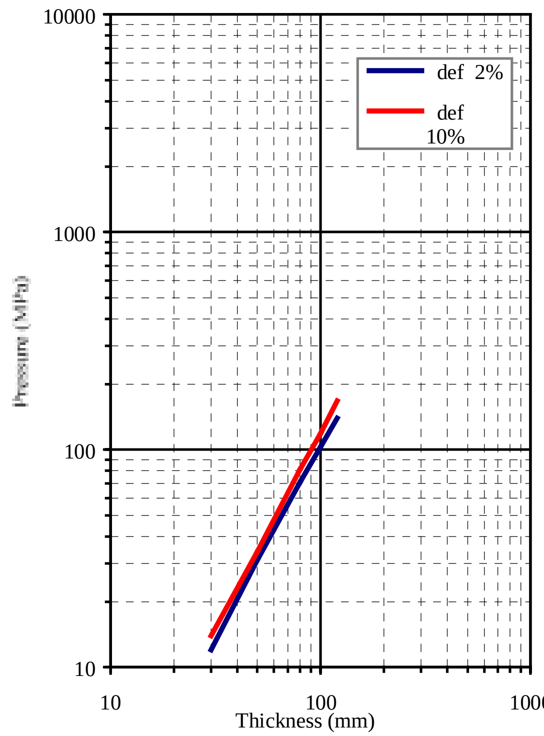

Fig. 7 Pressures inducing 2% and 10% strains

Required Thickness

For all cylindrical wall thicknesses between 30 and 120 mm, with 20% thicker flat ends, the critical buckling pressures clearly exceed those needed for triggering plastic collapse (see Fig. 8). However, the power laws describing the pressures required to develop the first buckling mode and peak strains of 2% grow with different exponents: 2.6 and 1.7, respectively. Thus, if those laws remained valid outside the thickness range studied, buckling would start preceding plastic collapse for wall thicknesses below about 10 mm.

DYNAMIC DEMANDS

On their way to the repository, canisters start by arriving empty at the surface facilities. Eventually, they are placed, closed and containing four fuel elements, inside the guide tube in a gallery of the repository. Their itinerary, described by AGP - Ingeniería de Proyecto[5], has been carefully studied in order to determine the accidental impacts that required evaluation. Only two accidents can be discussed here for reasons of space. The report mentioned earlier[1] includes many others, such as accidental drops of the canister inside and outside the overpack, drops of the lid onto the canister with various attitudes, etc.; they all indicate a suceessful performance of the canister.

Impact on a Punch

This postulated accident covers the effects of small drops of the canister onto strong rigid elements. It is idealized as a 1 m drop onto a 15 cm square punch. The impact velocity is then 4.42 m/s; the punch is assumed to encounter the canister at the centre of the cylindrical wall.

The analyses were conducted with ABAQS/Explicit[8]. A mesh, provided with greater detail where the higher stress and strain gradients are expected, was constructed to represent one quarter of the canister. Three cases, with wall thicknesses of 80, 100 and 120 mm, were analysed.

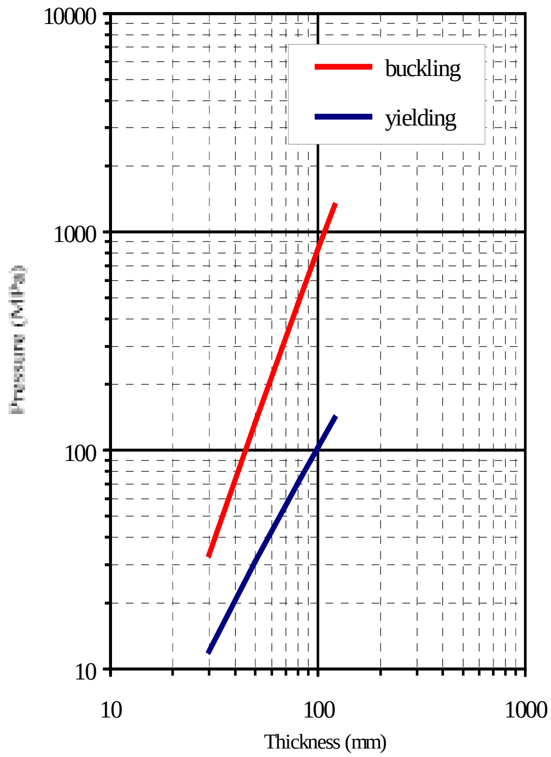

Fig. 8 Thicknesses required to avoid buckling and yielding

Fig. 9 shows a perspective view of the mesh with the plastic strain contours for the 100 mm wall thickness. The peak strain produced in the wall is 4.8% and the size of the indentation reaches 7.7 mm. Plastic deformations can be seen to concentrate in the region of the wall being contacted by the perimeter of the punch.

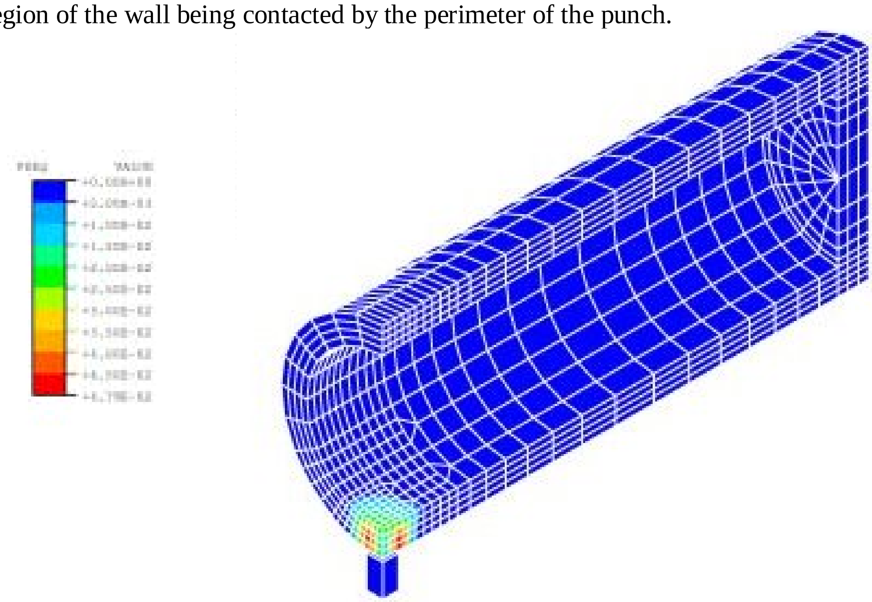

Fig. 9 Plastic strains. Perspective view

The peak plastic deformations are only moderately affected by changing the wall thickness; peak strain values are comprised between 4.8% and 5.2% for all three cases studied. It can be noticed that a greater thickness implies a greater mass and therefore a greater impact energy, since the impact velocity remains the same. However, the wall strength increases faster than the impact energy; as a result, the indentation depth, which reaches 9.1 mm with 80 mm walls, decreases to 7.1 mm with 120 mm walls.

Overturning

In this postulated accident, the canister is initially empty, open and standing upright. It is then assumed to overturn, thus causing severe effects on the open end when it impacts the rigid floor. The question is whether distortions will be sufficiently small to allow reusing the overturned canister.

A frictionless contact was assumed between the canister and the floor, thus maximising the impact energy. With this assumption, impact occurs with a vertical translational velocity of 5.81 m/s and with 2.73 rad/s for the rotational velocity. The frictionless contact leads to zero translational velocity in the horizontal direction.

Again, 80, 100 and 120 mm wall thicknesses were studied. For the case of 120 mm walls, Fig. 10 presents the plastic deformations, which clearly reflect the strong ovalization undergone by the open section of the canister upon impact with the rigid floor. The flexibility in bending of the final open section leads to only moderate plastic strains (less than 1.5%) while the geometric distortions are considerable: in the 80 mm canister, the vertical diameter permanently shortens 10.5 mm, while the horizontal one elongates 9 mm. For comparison, the corresponding values are 9.5 and 8.0 mm in a canister with 100 mm walls and further decrease to 8.5 and 7.5 mm with 120 mm walls.

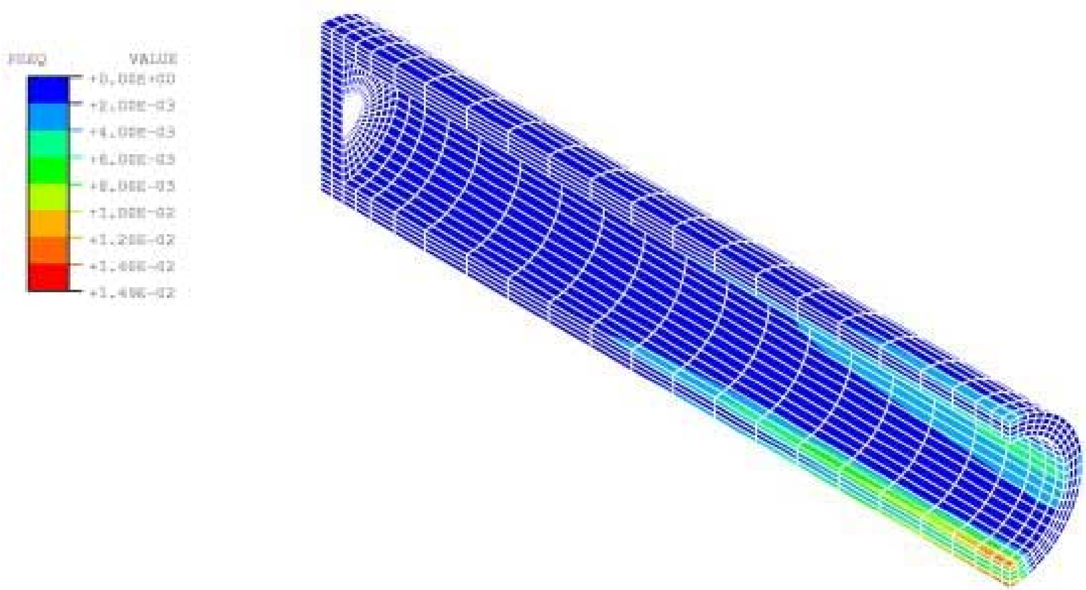

Fig. 10 Plastic strains. Perspective view

CONCLUSIONS

The effects of various physical demands on a specific type of storage canister have been analysed, including thermal and mechanical demands, both static and dynamic. The main conclusions follow:

- Peak surface temperatures in the canister occur in the cylindrical wall and reach 107°C. Thermal stresses are negligible. The thickness of bentonite experiencing over 100°C extends some 6 cm near the centre of the cylindrical wall and 2 cm at the flat ends of the canister.

- Increasing external pressures always causes plastic collapse before elastic buckling develops, at least for all wall thicknesses beyond 10 mm. The pressure required for plastic collapse is 103 MPa with 100 mm thick walls; the required pressure grows with wall thickness following a power law with exponent 1.7.
- Accidental 1 m drops of the canister onto a square punch do not threaten containment, but the plastic deformations caused reach about 5%. The peak indentation decreases from 9.1 mm with 80 mm thick walls to 7.1 mm with 120 mm walls, although the peak strains developed vary little over this range of thicknesses.
- The main result of an overturning impact is the ovalization of the open end. For wall thicknesses between 80 and 120 mm, plastic deformations are about 1.5–2% and the shortening of the diameter of the open section ranges between 8.5 and 10.5 mm.

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