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Thermo-mechanical behaviour and leak-rate prediction of a pre-stressed containment in case of an accident

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ABSTRACT: The evaluation of the leak rate of a reactor containment, of a steam-air mixture, corresponding to faulty conditions, is the purpose of the MAEVA experiment, performed by EdF. Somme predictive calculations have been made in the framework of a European benchmark exercise. In this paper, after having recalled the problems linked with the safety of containment s, the model chosen to calculate the leak in the current part of the containment is presented. The choice of the model has been directed on one hand by simplicity and on the other hand by the search of a solution enabling the calculation of a flow rate in a through crack. The results obtained are displayed and compared to those of other participants as well as to the experimental ones when available.

1 INTRODUCTION

The concrete containment of a nuclear reactor is the last barrier against a potential release of radionucleids in the biosphere, in case of an accident. Therefore it is of utmost importance to appraise the safety level of the containment, and to evaluate the leak rate if a through crack does occur. In France, many containment s are made of prestressed concrete, in order to sustain a more important internal pressure and also to improve the tightness of the containment. Under normal conditions, the water in the primary circuit is at a temperature of 320 C and a 15 MPa pressure. In case of a rupture of this circuit, the water will vaporize in the containment and lead to an internal thermal and pressure loading. The major question is then to predict the cracking of the containment and to evaluate the leak of an air-vapor mixture through the cracks. In particular, one scenario considered is the plugging of the through crack as by condensed water, thus reducing the leak significantly. This phenomenon has already been studied and checked on samples in laboratory experiments, but it has never been verified on full scale structures. This is the reason why the French utilities EdF and the Nuclear Safety Institute have decided to build and test a moke-up called MAEVA, representative of a portion of a nuclear reactor prestressed containment. In parallel, a European project, called CESA, was launched in order to organize predictive calculations in the framework of a benchmark, together with accompanying studies. The calculations which are presented in this paper have been performed in this framework, and compared to those produced by other teams, as well as to experimental results when available. In the following, the MAEVA moke up will be first presented together with the anticipated loading scenario. Then, the modeling methodology, followed to predict the moke-up leak rate will be detailed. Finally, the obtained results will be presented and discussed.

2 DESCRIPTION OF THE MAEVA MOKE-UP

2.1 General objectives of the moke-up

The leak of a containment may be partly attributed to the current part, through the connected porosity and microcracks of the concrete, and partly to various critical zones such as the interfaces between concrete and metallic penetration. The application of a permanent prestressing to the containment is expected to resist an internal pressure increase, and to reduce the containment leak rate. In case of an accident, some cracks are likely to develop through the thickness of the containment, increasing highly the leak rate.
Under such circumstances, the fluid inside the containment will be a mixture of air and steam. Therefore, one possible scenario, which is advocated

by the French utilities EdF, is that water plugs may form in the containment cracks, leading thus to a reduced leak rate, compared to an air leak rate.

In order to check this assumption on a real size structure, a portion of a cylinder of thickness 1.20 m was selected. The internal radius is 8 m and its height is 5 m. Concrete slabs are placed at the two ends to create a close space. They are tied by 4 prestressed concrete columns, in order to resist the pressure load. The connection between the cylinder and the slabs is achieved by means of neoprene pads.

In order to reproduce the state of stresses observed in a real containment, the cylinder is prestressed in both the hoop and vertical directions. An external wall is placed all around the cylinder to capture the eventual leak from the containment.

A general view of the MAEVA moke-up is shown on the figure 1.

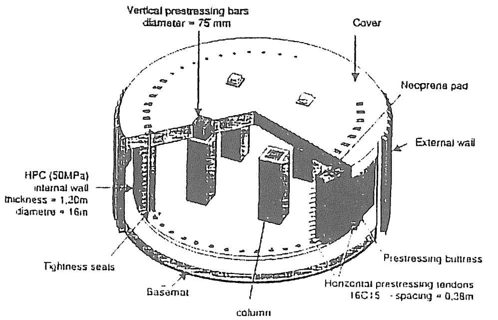


Figure 1. MAEVA Moke-up

Because of the high cost of such a moke-up, it has been decided to test simultaneously four zones, corresponding respectively to the current zone, a zone with a circular opening of 1.4 m diameter, and two zones with special internal composite liners. For the purpose, the moke-up external wall has been divided into four independent zones where the leak is being measured, as shown on figure 2.

The vertical prestressing is achieved by means of 70 vertical bars of 75 mm diameter, which are free to move in their sleeves. On the contrary, the hoop prestressing is achieved by means of two sets of adherent cables, type 19T15, located at radii 8.64 m and 8.96 m. Moreover, a large amount of reinforcing bars has been put in. A schematic view of all these elements in the current zone is displayed on figure 3, and will help the understanding of the model proposed later on.

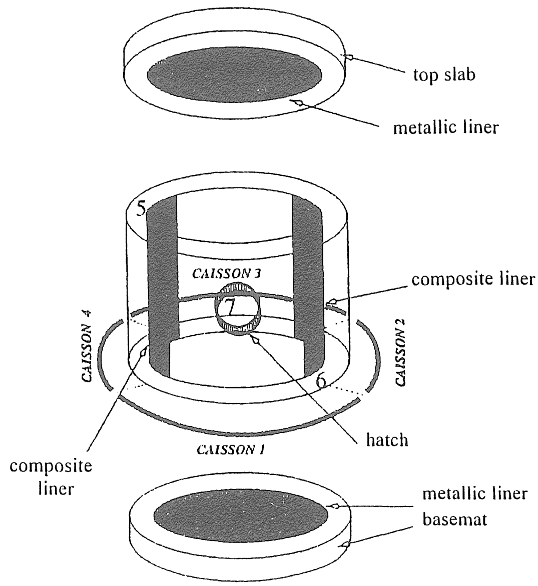


Figure 2. Principle of the leaks measurements

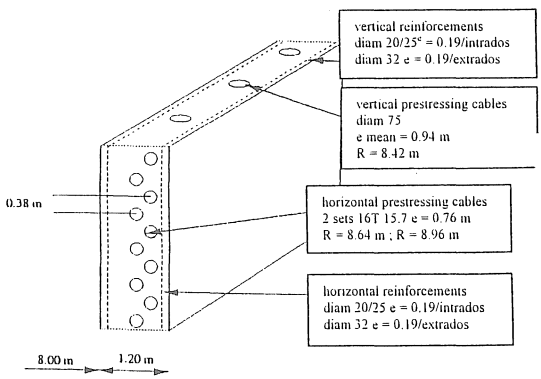


Figure 3. Layout of the prestressing cables and reinforcements

2.2 Loading sequences and measurements

In a first stage, the containment is prestressed. The mean stresses thus obtained are -5 MPa in the hoop direction and -3 MPa in the vertical direction.

Then, two types of loading have been considered, corresponding respectively to a design based accident (0.65 MPa internal pressure and 160°C temperature) and to a severe accident (1 MPa internal pressure and 180°C temperature). In both cases, the containment is filled with an air-steam mixture. In order to compare to a pure air leak, each of these accident stages are preceeded and followed by an air pressure test. The final loading sequences are shown on the figures 4 and 5.

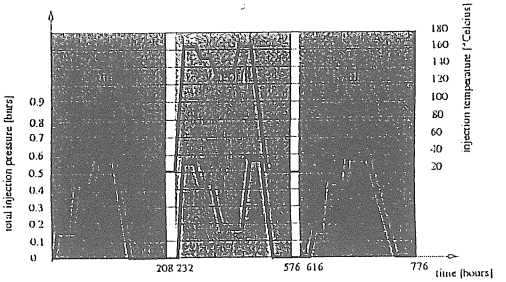


Figure 4. Design based accident, $P \leq P_{design}$

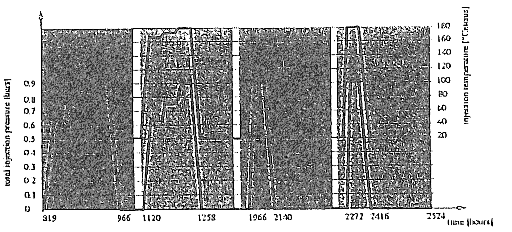


Figure 5. Severe accident, $P \geq P_{design}$

During the tests, displacements, strains and temperatures are recorded at various points in the containment. Moreover, two vertical prestressing cables have been instrumented (Martin Granger, 1996). The leak is evaluated in each caisson, from the measures of pressure, temperature, relative humidity as well as mass of condensed water on the walls.

3 MODELING METHODOLOGY

3.1 Basic assumptions

In view of the leak rate calculation, the stress has been laid upon the prediction of the cracks development in the moke-up. Therefore, couplings between the various phenomena have been treated in a sequential manner as follows:

- determination of the temperature distribution histories,
- calculation of the thermomechanical response of the containment, to the accidents loading, and prediction of possible cracks,
- calculation of the containment leak rate, once the flow path is known.

Because of the complexity of the moke-up, it was necessary to make some choices and some simplifying assumptions.

First, we were interested only in the leakage in the current zone. Secondly, we assumed that, because of the important vertical prestressing, there will be no horizontal cracks, the through cracks being located in meridional planes. Moreover, we also assumed that those vertical cracks will be triggered by the geometrical singularities created by the holes of the vertical prestressing bars.

Assuming uniform behaviour for the vertical prestressing bars located in the current part of the containment enables to reduce the model to the portion surrounding such a bar.

Finally, the model adopted is simply a bidimensionnal slice located at cylinder mid height, and surrounding the hole of the vertical bar (by symmetry, only a half of it is considered).

A view of the model with respect to its environment, is displayed on figure 6.

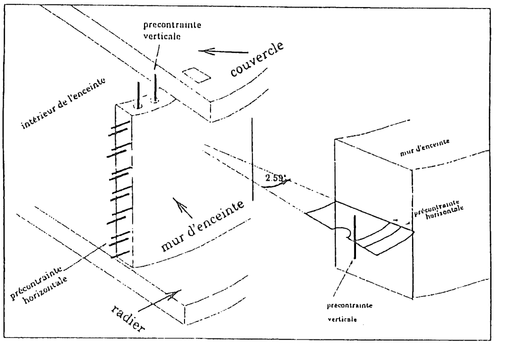


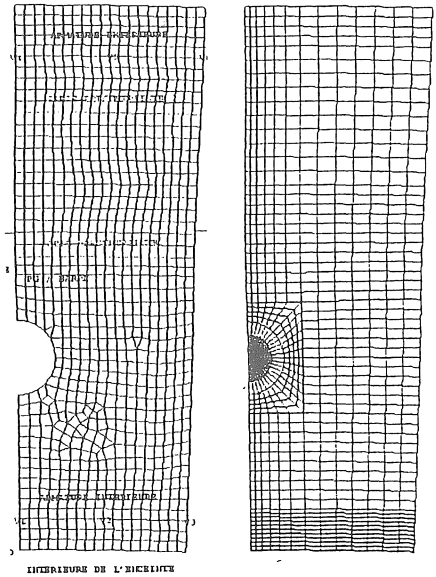
Figure 6. View of the 2D model considered in the analysis

Of course, such a model may not represent the complexity of the real structure. However, contrary to models of shell type, proposed by other teams for the containment, it is capable of reproducing the development of cracks in the wall thickness, which is, in our opinion, the key factor for the prediction of a path, necessary for a subsequent leak calculation.

3.2 Mechanical model

The mesh of the bidimensional slice is made of 1008 linear triangular and quadrangular elements, of two node bar elements for the horizontal prestressing and reinforcing bars and of one node elements (perpendicular to the plane of the slice) for the vertical prestressing and reinforcing bars. The mesh is shown on figure 7.

In order not to overconstrain the model in the vertical direction, a generalized plane strain has been assumed (Combescure 85), the section being allowed to rotate around a point located where the neoprene pad reacts. The vertical prestressing bar is also placed there.



Mechanical mesh Thermal mesh

Figure 7. Meshes used for the model

Concerning the materials behaviours laws, classical elasto plastic models with linear kinematic hardening are used for the horizontal reinforcing bars, whereas the vertical bars and prestressing cables are assumed to remain elastic in view of their high yield stress (835 MPa and 1655 MPa respectively).

The concrete is modeled by means of an elasto plastic fracturing model, using on one hand the smeared representation of cracking (Rots J. et al, 1985) and on the second hand, the Hillerborg fictitious crack concept (Hillerborg A. et al., 1976) in order to dissipate the good energy independently on the mesh size.

The main ingredients of the model are inspired from Ottosen (Dahlblom & Ottosen, 1990) and consist in:

- strain partitioning: $\varepsilon = \varepsilon^{e} + \varepsilon^{p} + \varepsilon^{c}$
- cracking occurs according to a maximum principle stress criterion:

$$\max_{i=1,3} \sigma_i \leq R_t$$

- a maximum of 3 orthogonal cracks may form at a given point,
- a simple linear post pic behaviour is assumed, including possible closing and reopening of the crack (unilateral effect) as shown on figure 8.

Concerning the boundary conditions, symmetry conditions are prescribed on the two lateral sides of the model.

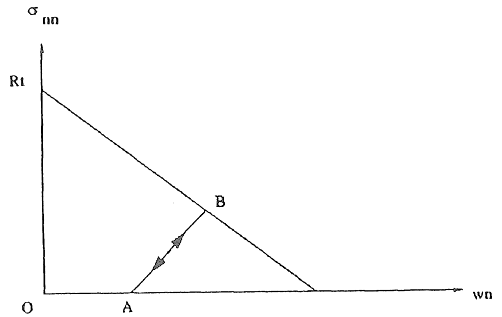


Figure 8. Concrete behaviour along the normal to a crack

The various mechanical properties used in the computation are summarized in table 1.

	Concrete	Vertical cable	Horizontal cable	Vertical reinfor-cements	Horizontal reinfor-cements
E	34.231 GPa	205 GPa	190 GPa	200 GPa	
ν	0.2	0.3			
R_t	3.423 MPa	835 MPa	1655 MPa	500 MPa	
Gf	100 N/m				
α	10^{-5}°C				
Cross section		20.925 cm^2	144 and 168 cm^2	1.57 and 4.91 cm^2	21 cm^2

Table 1. Mechanical properties used in the calculation

Comparisons performed in the elastic domain, with more sophisticated models have shown that radial and circumferential displacements and stresses were correctly predicted by our simple 2D model. There are more discrepancies along the vertical direction, but this is not our main concern as outlined before.

3.3 Thermal model and results

The mesh used for the thermal analysis is different from the mechanical one (see figure 7) in order to account for the inner thermal gradient, as well as the heterogeneity caused by the vertical prestressing bar. Variable thermal conductivity and specific heat, derived from (Noumowé et al., 1996) and Eurocode 2 have been introduced.

Among the important features for the non linear thermal analysis, are the inner and outer boundary conditions.

Indeed, exchange boundary conditions are prescribed, with a variable exchange coefficient depending of the flow regime and the fluid nature in the containment. Outside the containment, the fluid is maintained at a 60°C temperature and a forced convection is prescribed, while inside, a natural convection is assumed with an exchange coefficient varying between 8 W/m^2/°K (air at rest, at 20°C) and 460 W/m^2/°K (during accident at T = 160°C).

As major results, let us compare the temperature profiles through the thickness, at two different times, calculated by our 2D model and by models (in general axisymetric or three dimensional) of other participants.

A general agreement is observed on the figures 9 and 10, the major discrepancies coming from too coarse meshes.

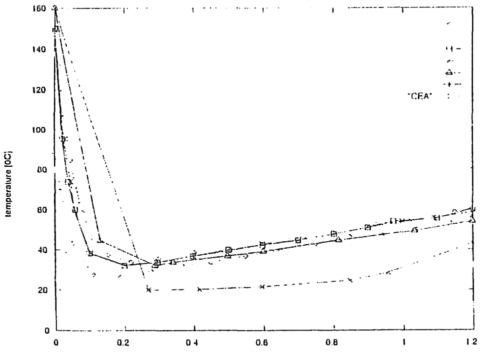


Figure 9. Temperature profile across the thickness at t = 240 h

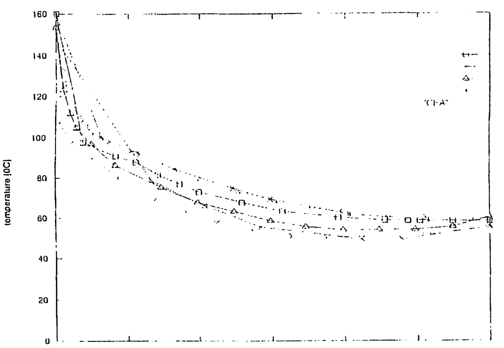


Figure 10. Temperature profiles across the thickness at t = 256 h

3.4 Mechanical results

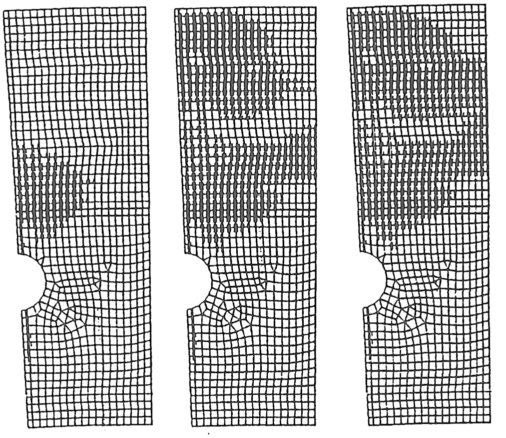
The non linear mechanical calculation is performed afterwards, using the previously determined temperature histories. All the loading sequences have been followed.

As anticipated, the first crack occurs at the hole edge, in the plane of symmetry, at time t = 236 h, that is during the first hold period following the pressure and temperature increases.

Then, the crack tends to propagate from below and above the hole, until it reaches the hoop prestressing cable (see figure 11). There, the crack starts to smear in the concrete around the cable, due to the hypothesis of perfect bond between the cable and the concrete.

When the pressure and temperature decrease from this first plateau, the cracks have reached the outer wall of the containment, and have smeared around the prestressing as well as reinforcing bars.

However, the openings of the cracks displayed on figure 11 are very different from place to place.



t = 240 h t = 256 h t = 269 h

Figure 11. Development of cracks during the first pressure and temperature increase

Afterwards, the cooling of the structure causes the occurrence of cracks at the inner wall, together with sub-horizontal cracks at the edge of the hole. At that time, the previously developed cracks along the prestressing cables, are closed. Finally, from t = 552 h, the cracks pattern does not evolve any more, and there is no continuous crack path through the thickness at the end of the design based accident scenario.

The comparison of the radial displacement, at mid-height of the containment, as predicted by the various participants to the benchmark exercise, shows a fair agreement, if the lower curve is excluded because of a too low Young's modulus considered (Granger et al., 1999).

Under the severe accident loading protocol, the pressure loading itself (air at room temperature inside the containment) does not create any new crack. The major cause of concrete cracking is clearly the thermal loading: During the temperature variations, the opening of the macrocrack located between the two horizontal prestressing cables, is directly proportional to the temperature variations. The wider crack opening ($1.15\ 10^{-4}$ m) is obtained at 1168 h.

However, after the first pressure and temperature peak, there is still no through crack. This one is obtained during the second peak, at t = 2026 h. The corresponding cracks pattern is shown on figure 12 together with a view of the cracks which have a zero residual tensile strength (i.e. their maximum opening is superior to 2 Gf/R_t). This information will be used for the calculation of the leak rate, as explained in the next paragraph.

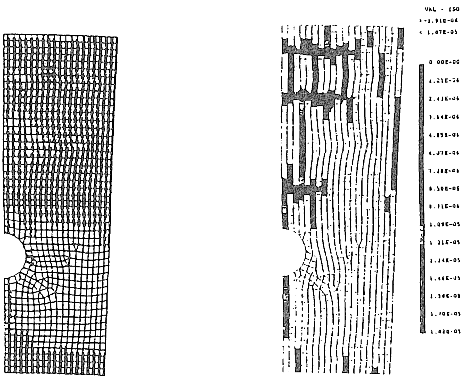


Figure 12. Cracks pattern at t = 2026 h
(a) Cracks distribution
(b) Location of fully developed cracks (no more tensile strength)

4 LEAK RATE PREDICTION

This stage is doubtless the most difficult one in the benchmark exercise. Indeed, from a literature survey, it appears that the problem of diphasic flows in fracture is still under study. Therefore, it is clear that the prediction of the flowrate in the framework of our model may only be qualitative, and is based on many assumptions which would require additional research investigations. The methodology we have followed consists in using a model developed for a single crack, and validated against experiments (Caroli et al., 1993).

4.1 Model of steam leakage through a crack

First, the crack is supposed to be rectilinear, with variable aperture e(x), in a bidimensional medium, as sketched on figure 13. The surrounding concrete is considered as impervious, but may exchange heat with the fluid in the fracture.

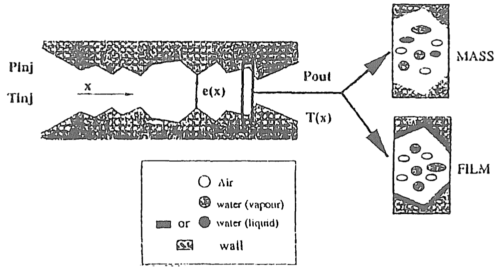


Figure 13. Fracture idealization for leak rate prediction

In view of the thermal characteristic times, the flow may be considered as steady. A mean value of the flow is considered for each cross section, and the gaz and liquid are supposed to have the same velocity and temperature. Phase change within the fluid is accounted for as well as the head loss due to the friction on the fracture walls. Finally, air and steam are considered as perfect gases.

Concerning the boundary conditions, the fluid pressure the temperature and the steam partial pressure are prescribed at the inlet of the crack, as well as the fluid pressure at the outlet. The model then calculates the profiles of pressure, temperature and steam volume fraction along the crack, at a given time.

4.2 Application to the cracked 2D model

In order to be able to apply the above flow model, it was first necessary to convert the previously calculated smeared cracking into a single localized fracture. This is the most questionable point in our approach. Some engineering judgment has been used as follows:

- from experimental observations, cracks are forming at the location of prestressing cables,
- only cracks showing a maximum opening superior to 2 Gf/R_t have been retained,
- around the sleeve of the vertical prestressing cable, the continuity of the crack has been postulated,
- finally, the thickness e(x) of the crack, supposed to l y in the symmetry plane, has been obtained by simply adding, for a given abscissa x, the openings of the selected cracks located there.

The figure 14 summarizes the different steps of this procedure.

From this, the flowrate in the crack can then the determined, as well as the total flowrate in the caisson, assuming a uniform flow rate on the height

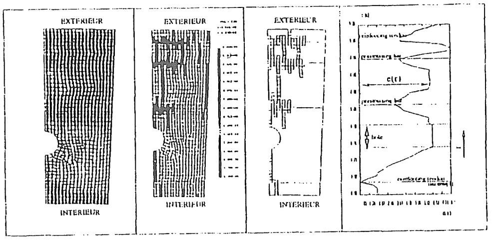


Figure 14. From smeared cracking to a localized crack
(a) cracks pattern
(b) cracks openings
(c) selected cracks forming the through crack
(d) equivalent crack opening

of the cylinder and for all the cracks supposed to form along the vertical prestressing cables. The final results are summarized in table 2.

Time (h)	Internal pressure (10^5 Pa)	Nature	Q (kg/s)	Minimum opening (m)
2017	8.8	air	$1.64\ 10^{-5}$	$0.203\ 10^{-5}$
2038	10	air	$1.5\ 10^{-2}$	$0.455\ 10^{-5}$
2110	4	air	$1.97\ 10^{-5}$	$0.831\ 10^{-6}$
2282	4	air+steam	$3.78\ 10^{-5}$	$0.831\ 10^{-6}$
2296	8.2	air+steam	$1.75\ 10^{-4}$	$0.831\ 10^{-6}$
2302	10	air+steam	$4.57\ 10^{-4}$	$0.831\ 10^{-6}$

Table 2. Total flow rate in the caisson, at various times

As already observed on laboratory tests, these calculations show a strong reduction of the flow rate between an air leak (11.5 % per day) and a mixture leak (0.8 % per day). A careful examination of the steam volume fraction along the crack indicates that in some portions, in particular where the thickness is reduced at the inner reinforcing bars, the vapor condenses.

5 CONCLUSION

Contrary to the thermal and also the mechanical results, the leak rate predictions, which were the ultimate goal of the benchmark exercise, show a very wide scatter. Some participants were even not able to perform such calculations. This clearly underlines the difficulty of such predictions and the need for further research work in this complex domain.

Concerning our model, we believe that it was well fitted to the prediction of phenomena taking place in the thickness of the wall, within the limits of our basic assumptions. Of course, the real containment is much more complex, and the 2D model can not b ing definitive answers. For example, even in the current zone, the behaviour of the containment is not uniform on the height, and the shape of the cylinder changes from a barrel to a diabolo, according to the thermal loadings. Moreover, since an important part of the leak comes from the hatch zone, it will be necessary to turn to a three dimensional modelling to produce more realistic predictions of the leak rate.

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