Effects of Fluid Transport on the Structural Integrity of Concrete Nuclear Pressure Vessels

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1. INTRODUCTION

Concrete is a complex, multi-phase material, consisting of aggregates bound by a highly porous, hygroscopic solid cement paste skeleton, which can be up to 68% pore space by volume (~28% gel pores ≤ 2.6nm in diameter and up to 40% capillary pores in the range of 1μm in diameter). Under normal environmental conditions the pore space is filled with fluids, typically including dry air and water. The water is characteristically present in the form of vapour, liquid and adsorbed water, which is physically bound onto the surface of the solid skeleton.

When exposed to high temperatures, heat is conducted and convected through the material, leading to various changes in the fluids, including phase changes (both evaporation and condensation) and transportation, through several mechanisms including pressure driven flow and diffusion. Furthermore, the fluid content may be affected by temperature dependent changes in the structure of the concrete. These may be chemical changes such as (de)hydration, or physical changes, for example to the porosity and permeability of the concrete, all of which have a direct effect on the fluid transport behaviour.

As these processes act on the pore fluids, they result in changes to the pore pressures. These pressures have a direct mechanical affect on the concrete in that they modify the effective stress state. Though this mechanism, pore pressures are generally thought to be a major contributing factor to the development of damage, and spalling.

Concrete can experience high temperatures through a number of accidental or deliberate scenarios, e.g. fire or high temperature industrial applications. In all these scenarios the concrete and the fluids within it will, to some degree, undergo the processes described above and damage may occur. The severity of the damage will depend on numerous factors including the intensity of heating, the material and physical properties of the concrete and the environmental conditions to which the concrete is exposed over its lifetime.

One such problem is that of concrete nuclear reactor pressure vessels (Figure 1). During their normal working life the insides of these vessels are exposed to temperatures up to ~80°C, while their outsides remain at atmospheric temperature. Some of these vessels have now been in operation for more than 30 years and it was the task of the MAECENAS project (Modelling Ageing in Concrete Nuclear Power Plant Structures) to study the effects that the operating conditions have had on the concrete over this time. Although beyond the scope of the MAECENAS project, another consideration for these vessels is the possibility of unplanned excursions to higher temperatures (up to ~400°C), as may be experienced due to a loss of cooling water.

This work focuses on the heat and moisture transport in concrete nuclear pressure vessels and the direct effect that this could have on their structural integrity, both under normal operating conditions and under temperature excursions. The investigation was carried

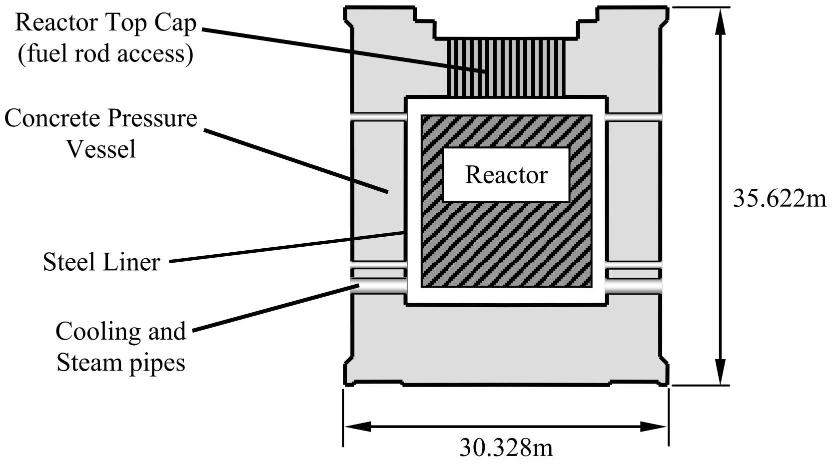

FIGURE 1. Section through Cylindrical Concrete Nuclear Reactor Pressure Vessel

out using the fully coupled hygro-thermal-mechanical numerical model developed during the MAECENAS project and described in detail in Davie et al. [1]. Although reference is made to the mechanical consequences of the transport behaviour, mechanical behaviour was not considered explicitly in this study.

2. NUMERICAL INVESTIGATION

Two finite element meshes, representative of a specific type of nuclear pressure vessel were developed for use during the MAECENAS project (See Figure 2a & b). Due to the complexity of the coupled hygro-thermal-mechanical model, the size of the meshes and the number of time steps required, a single analysis with the axi-symmetric mesh on the computing facilities available†, could take approximately 2 weeks to complete. For that reason, a smaller mesh, which was equivalent to a slice through the full axi-symmetric mesh (Figure 2c), was created for this work.

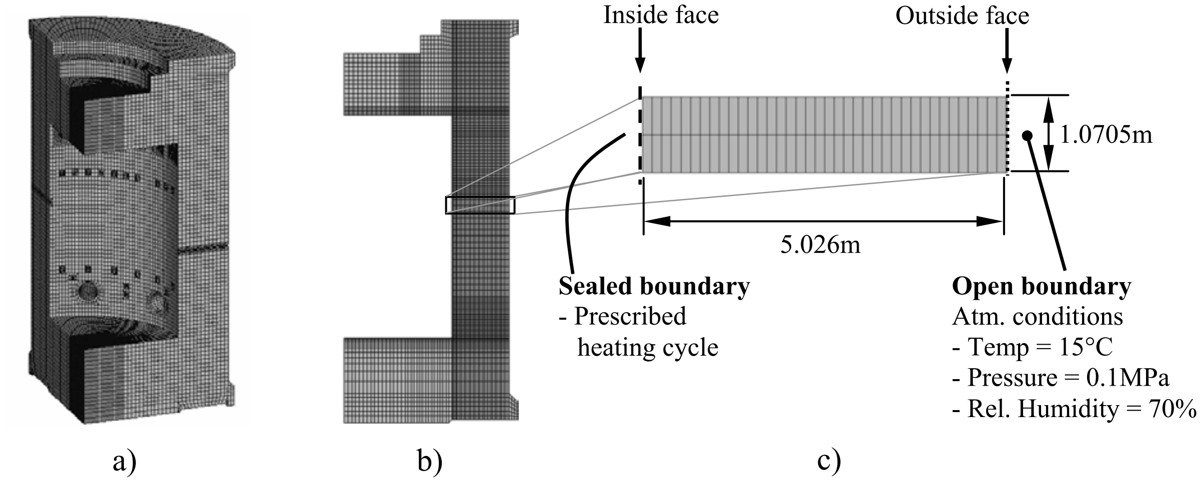

FIGURE 2. Pressure Vessel FE meshes a) One Quarter 3D Mesh (20 noded elements), b) Axi-symmetric Mesh (8 noded elements), c) Axi-symmetric 'Slice' Mesh (8 noded elements)

To reproduce the external conditions experienced by a nuclear pressure vessel, the outside face of the mesh was given Cauchy type boundary conditions to simulate the free exchange of heat and fluid with the atmosphere, while for the inside face, only a prescribed (Dirichlet type) temperature boundary was defined. Boundary conditions were not defined for the fluid phases in order to represent the sealed conditions imposed by the steel liner on the inside of

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† This work was carried out on a 3.0GHz Pentium 4 machine with 2Gb memory, running Linux.

the vessel. The top and bottom sides of the mesh were considered as symmetric boundaries to represent the large, continuing structure above and below the ‘slice’.

Using this model, two parametric studies were carried out. The first was comprised of 5 analyses in which a 33 year heating cycle (from data recorded in an existing pressure vessel) (Figure 3a) was applied to the inside face and the resulting fluid transport behaviour monitored. The parameters investigated were the initial permeability, K_0, and the initial porosity, ϕ_0, of the concrete. It should also be noted that both permeability, K, and porosity, ϕ, increase irreversibly with increasing temperature. The second study involved 2 further analyses in which heating cycles representative of temperature excursions were applied (Figure 3b & c) and again the resulting fluid transport behaviour was monitored. All other parameters were kept constant. A summary of all the analyses can be found in Table 1.

Study	**Analysis**	**Initial Permeability, K_0**	**Initial Porosity, ϕ_0**	**Temperature Profile**
1	1	5.0×10^{-17} m^2	0.099	Standard
1	2	1.0×10^{-21} m^2	0.099	Standard
1	3	2.0×10^{-18} m^2	0.099	Standard
1	4	2.0×10^{-18} m^2	0.090	Standard
1	5	2.0×10^{-18} m^2	0.120	Standard
2	1	2.0×10^{-18} m^2	0.099	Excursion 1
2	2	2.0×10^{-18} m^2	0.099	Excursion 2

TABLE 1. Summary of Analyses for Parametric Studies

As discussed previously, the pore pressures in the concrete were of particular interest. However, for simplicity only gas pressures, which can be shown to be largely analogous with overall pore pressure behaviour, are given here.

STUDY 1: As can be seen from the results shown in Figures 3d & e, the gas pressures predicted at the inside face of the pressure vessel over its 33 year life, vary considerably depending on the initial values of both permeability and porosity. As would be expected, both higher permeabilities and higher porosities lead to lower maximum predicted pressures as fluids can move more easily away from the hot face, towards the atmosphere. Despite the variations, the magnitudes of the gas pressures (~0.2-0.8MPa) are generally not high enough to exceed the tensile strength of the concrete and cause structural damage on their own. However, in conjunction with mechanical stresses produced during operation of the reactor, these pressures may become significant and should be taken into account. Of more immediate concern is the gas pressure predicted with the lowest permeability (1.0×10^{-21}m^2). After 33 years this has reached ~1.4MPa and continues to rise. While not enough to cause fracture of the concrete on its own, this pressure may threaten the structural integrity of the steel liner in the vessel. If this liner is ruptured, radioactive gases will escape into the concrete and eventually into the atmosphere.

While both parameters can be seen to have a significant effect, the porosity can often be related to the design mix of the concrete and is therefore readily known and accounted for. However, values for permeability are less easily estimated and vary considerably (over about 4 orders of magnitude) in the literature [2, 3]. This uncertainty is clearly a concern when its potential effects are considered.

STUDY 2: As can be seen from Figure 3f, the temperature excursions have a significant effect on the predicted gas pressures. During both excursions, pressures of ~10MPa were predicted. These values are such that they will potentially compromise the structural integrity of the pressure vessel both by causing fracturing, since the pressure will exceed the tensile strength of most concretes, and by rupturing the steel liner.

A further point of note is that in both cases the gas pressures predicted after the temperature excursion are considerably lower than those predicted under the normal operating heat cycle (Figure 3f inset). This is because the permeability and porosity of the concrete have been increased significantly by the irreversible damage caused by the temperature excursion and the fluids can more easily flow away from the inside face of the pressure vessel. It should also be noted, however that, although the temperature excursions reached the same temperatures and therefore caused the same permeability and porosity increases, the gas pressures predicted after the two incidents were different. This highlights the importance of considering the full heat and fluid transport history of a concrete structure when predicting the potential effects on its structural integrity.

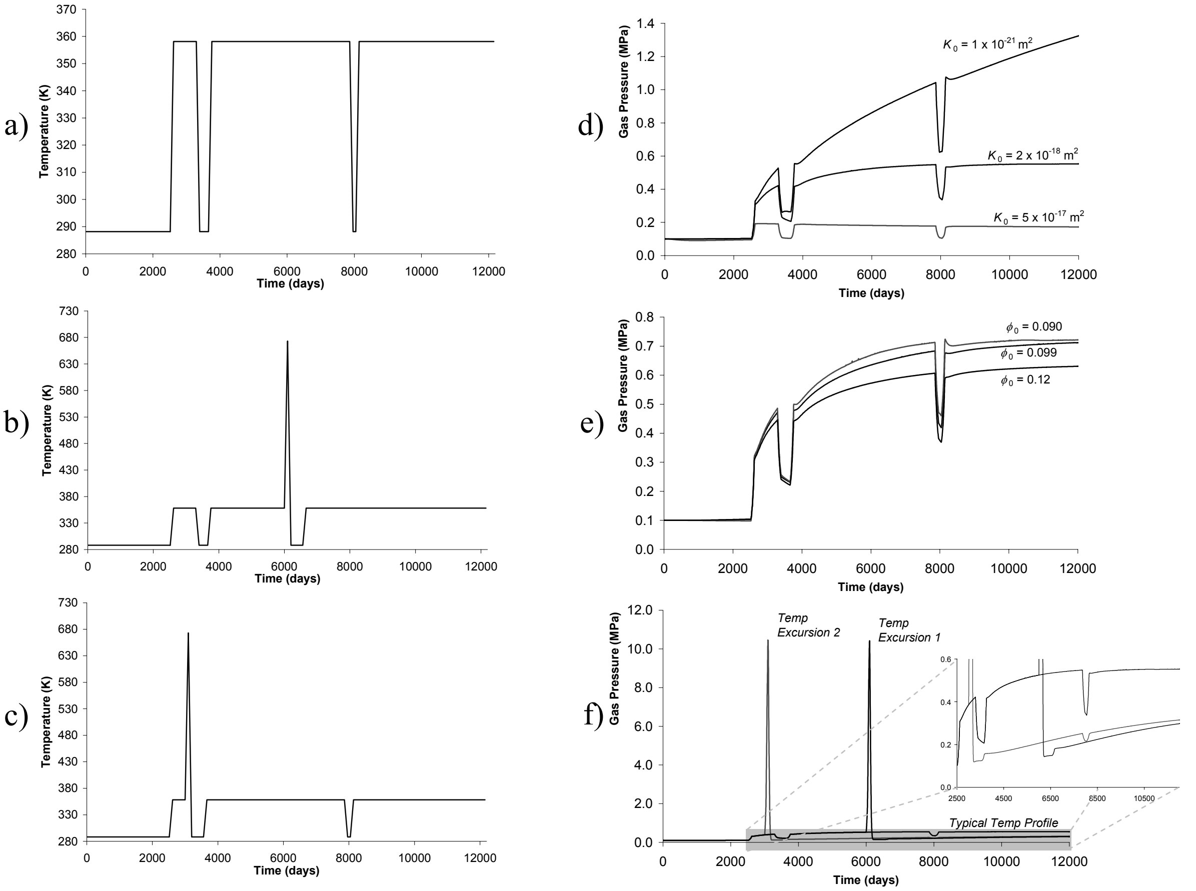

FIGURE 3. a) Standard Heating Cycle, b) Excursion 1 Heating Cycle, c) Excursion 2 Heating Cycle, d) Gas Pressure for Varying Initial Permeability, e) Gas Pressure for Varying Initial Porosity, f) Gas Pressure Under Temperature Excursions; All Applied/Recorded at Inside Face of Pressure Vessel

3. REFERENCES

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4. ACKNOWLEDGEMENTS

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