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SLOSHING EFFECTS IN INNOVATIVE NUCLEAR REACTOR PRESSURE VESSELS

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ABSTRACT

The reactor pressure vessel is a cylindrical shell structure which contains a rather large amount of liquid and many structures. Therefore, the fluid-structure interaction problems and the free oscillation of an incompressible liquid have attracted the attention because during a postulated earthquake (e.g. Design Basis Earthquake) the primary coolant surrounding the internals is accelerated and a significant fluid-structure hydrodynamic interaction is induced: in particular, the so called coolant "sloshing" influence on the stress level in the RPV.

This effect is mainly important in the case of liquid metal primary coolant case and its coupling with the reactor vessel and its internals are considered.

Numerical modelling proved to be very useful for the foreseen structures analysis because neither linear nor second-order potential theory is directly applicable when steep waves are present and high-order effects are significant.

In what follow numerical results are presented and discussed highlighting the importance of the fluid-structure interaction effects in terms of stress intensity and were also used in order to obtain a preliminary validation of the numerical approach/models in comparison with experimental data.

INTRODUCTION

Fluid-structure interaction problems have attracted a great deal of attention because of their wide range of applicability. Numerous physical phenomena provide examples of this interaction type, in particular in the event of earthquake.

The safety of liquid retaining structures subjected to a seismic loading is of great importance in regard to the hydrodynamic forces caused by sloshing and impulsive liquid motion determined by the fill levels containers oscillatory phenomenon.

The analysis of the liquid sloshing is very important in many engineering applications as in the field of Nuclear Power Plants (NPPs) structures, to evaluate the real capacity of dynamic loads bearing and related safety levels as NPP integrity of structures, systems and components must be ensured in case of any design condition in particular in the event of an earthquake [1]. Heavy metal primary coolant, which characterize some NPP type responds to dynamic motions, particularly to the seismic one, and when the excitation has a frequency near the natural one of the container system, waves some rather "violent" can form and impact to the tank walls.

In these cases sloshing loads may arise severe enough to cause structural damage. It is therefore necessary to take into account the sloshing effects at the design stage.

It must be pointed out however that realistic prediction are made particularly difficult by the non-linear nature of the phenomenon and by the large number of parameters affecting it, such as tank geometry, liquid-fill height, period and amplitude of excitation and position of the system rotation centre.

In this paper a preliminary application of the methodology to an innovative next-generation reactor eXperimental Accelerator Driven System XADS structure is presented.

This preliminary analysis is intended to evaluate the influence of the dynamic loads propagation from the ground to the Internals.

STRUCTURE AND MODEL DESCRIPTION

New reactor designs meet the criteria of sustainability (GEN-IV, 2002) and should be competitive, safe as well as proliferation resistant. Next-generation systems also have to reduce the amount and radiotoxic inventory of residual wastes destined to geological repositories. To achieve these goals, recycling of fuel and recovery of long-lived nuclides during reprocessing will be necessary.

This will not only reduce the radiotoxic inventory of the waste but also allow converting long-lived actinides into energy and/or in shorter level also.

An efficient use of fissile fuel resources together with the ability to burn its own high-level wastes and those coming from Light Water Reactors (LWRs) are primary design goals of several new reactor designs developed under the auspices of the Generation IV initiative [2].

XADS reactor type, showed in the following Figure 1 for instance, is characterized, from a mechanical point of view, by the relevant coolant and their own weight to which the structures are submitted.

In fact the Reactor Vessel itself is filled with about 2000 tons of liquid Lead-Bismuth eutectic that have to be transferred through the Annular Structure to the reactor building foundations. This aspect causes the Reactor Vessel and Annular Support to be the most critical objects in the design activity of the mechanical components, in particular the effect of this mass is amplified during seismic conditions.

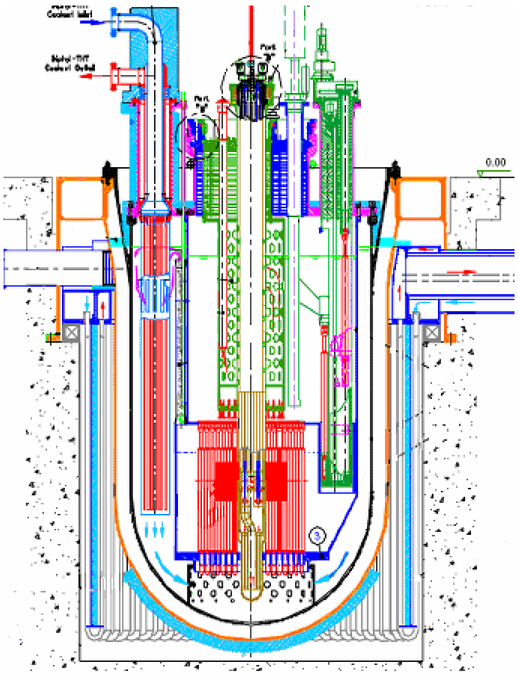


Figure 1 XADS Reference Configuration – Reactor Assembly

The pool-type, instead of the loop-type configuration, is chosen for XADS because of the possibility to contain within the main vessel all the primary coolant and of the large experience acquired with the design and operation of sodium-cooled, pool-type reactors. Both Reactor and Safety Vessel are composed of a cylindrical shell with a hemispherical bottom head. The upper part is divided into two branches by a “Y forged piece”: the inner cylindrical branch supports the Reactor Cover; the outer conical branch transfers the whole weight of the Reactor Vessel to an annular support.

The Reactor Roof ensures component support, reactor cover gas containment, and the biological protection.

To the purpose of this study a system constituted with three mutually interacting components were considered: the Reactor Vessel, the submerged structure, as for an example the core and its support, and the Safety Vessel too.

The Reactor Vessel (RV) is wrapped by the mentioned coaxial Safety Vessel (SV) and the two are supported by the same support named Annular Structure: the Safety Vessel is directly welded to it; the Reactor Vessel is connected by a bolted flange. The Internal Structure is located inside the Reactor Vessel and hangs from the Reactor Roof.

The choice of lead and/or lead-alloys (e.g. lead/bismuth eutectic) as coolants is motivated by good nuclear properties and thus, no intermediate coolant loop is needed. Argon is injected at the bottom of Riser Channels to increase the density difference between the cold LBE in the Down comer and the hot LBE-gas mixture in the Riser. The argon gas leaves the coolant at the free surface and escapes into the cover gas plenum [3].

MODEL DESCRIPTION

The first task in structural modelling is to develop a fixed-base model of the above mentioned reactor; in as much detail as necessary to define adequately the dynamic response due to Safe Shutdown Earthquake at all desired locations but reasonable limiting the considered details for calculation efficiency.

The XADS design is peculiar with respect to the traditional sodium cooled reactor design: the absence of a physical separation between hot and cold fluid plenum. The components considered are the following:

- Reactor and Safety Vessels;
- Reactor Internals;
- Molten primary coolant: Lead-Bismuth Eutectic (LBE).
- Cover gas: argon

Modelling of mentioned structures required the setting up of appropriate meshes assembled with suitable elements (as e.g. 3-D solid brick and/or shell type elements, available in the used finite element modelling code (FEM)) to represent the behaviour of each fluid-structure interaction [4]. The analyses were performed with some suitable simplified assumptions.

The Safety Vessel (Figure 2) was one of the main structures studied. It encloses the Reactor Vessel. As it was mentioned the SV is a welded structure made of a SS cylindrical shell and a hemispherical bottom. Unlike the Reactor Vessel, it is provided with four radial openings to grant access to the gap between the vessels for Inspection service. The main dimensions of the Safety Vessel are as follows.

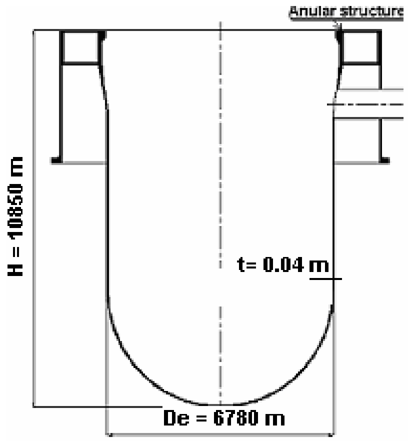


Figure 2 Safety Vessel and annular structure – Vertical Section

The Reactor Vessel (Figure 3) consists of a cylindrical shell with a hemispherical bottom head, without nozzle for out-of-vessel primary coolant circulation, and of an annular Y-shaped Support Structure. The upper part, already indicated as "Y forged piece", may be considered subdivided into two components: the outer conical one which transfers the whole weight of the RV/SV to a support named Annular Structure, and the inner cylindrical one which supports and sustains the Reactor Cover and the superstructures components.

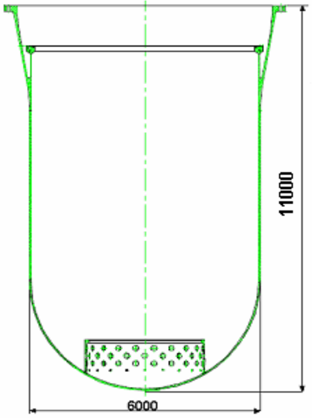


Figure 3 Reactor Vessel – Vertical Section

The cover gas argon was considered as a perfect gas.
Materials used in modelling the nuclear reactor components are type 304L and 316L SS; Lead-Bismuth Eutectic is the coolant fluid. The material properties for the Reactor and safety Vessel as well as for the lead-bismuth Eutectic and argon gas are shown in Table 1.

Table 1 Material properties

Material Properties	**Pb-Bi**	**Argon**	**Stainless Steel**
Density ρ (kg/m^3)	10730	3.0	7800
Young Modulus E (MPa)	-	-	210000
Bulk Modulus (MPa)	31490	-	-
Poisson coef. ν	-	-	0.3
Yielding stress σ (MPa)	-	-	240

ANALYSIS METHOD

As already mentioned due to the reactor vessel height, the large dead weight of lead and the large free surface of the molten coolant, seismic loading and sloshing may become very important.Seismic loading, due to LBE sloshing effect, may produce stresses exceeding the allowable limits in localized parts of the reactor Internals.

A scoping analysis has then been performed by the response spectra method, using the design basis earthquake ground motion spectra.

Analytical approaches and related asymptotic solutions to predict sloshing motion in fixed and moving tanks have been explored by several investigators, e.g. Faltinsen. As mentioned, the literature reveals that sloshing motion has been investigated with either vertical or horizontal excitation.

The present paper investigates numerically free surface sloshing in RV with a focus on moving liquid tanks mainly for horizontal excitation. The fluid inside the vessel is considered as incompressible not viscous and irrotational. The lateral acceleration, A_x is usually a function of time.

Assumed that the local velocity potential is φ(x, y, z, t) in a Cartesian coordinate system (x, y, z) with t that indicates the time, the fluid motion governing equations based on the potential theory are as:

$$\nabla^2\Phi = 0 \tag{1}$$

where Φ = Φ (x, y, z, t) is the velocity potential in the above Laplace equation. The kinematic boundary conditions are pure-slip on the free surface as:

$$\frac{\partial\xi}{\partial t} = \frac{\partial\varphi}{\partial y} - \frac{\partial\varphi}{\partial x}\frac{\partial\xi}{\partial x} - \frac{\partial\varphi}{\partial z}\frac{\partial\xi}{\partial z} \tag{2}$$

where ξ = y is the free surface elevation above the still liquid level. The dynamic boundary condition on the free surface is:

$$\frac{\partial\varphi}{\partial t} = -\frac{1}{2}\left[\left(\frac{\partial\varphi}{\partial x}\right)^2 + \left(\frac{\partial\varphi}{\partial y}\right)^2 + +\left(\frac{\partial\varphi}{\partial z}\right)^2\right] - g\xi + \tag{3}$$

$$- A_x x - A_z z$$

In the above equations, g is the acceleration of gravity, n is the normal vector, t is the time.

The initial values of velocity potential and free surface height are set to zero, which corresponds to still liquid beginning condition.

The boundary conditions on the curved walls may be considered an example of the non-linearity effects caused by the geometrical shape boundary conditions on the free surface, as well as the time-varying integration domain for the time-varying free surface contribute to the major difficulties in obtaining the numerical solution for sloshing behaviour in cylindrical vessel.

The basic assumptions for both fluid and structure problems are the following ones:

- Fluid have an elastic, linear, isotropic behaviour;
- RV, SV and Internal structures have a linear elastic perfectly plastic as well as isotropic behaviour;
- Fluid and structure exchange mechanical energy at the fluid-structure interface.

The theoretical analyses of fluid sloshing in a tank, subjected to seismic loads account for fluid pressure due to four different contributes depending by ground acceleration (impulsive pressure) and the rigid tank assumption (convective pressure) as well as by the liquid surface displacement (fluid pressure) and the tank deformation (due to the fluid pressure itself) too.

It maybe worthy to note that on the contrary in the carried out preliminary analyses, the fluid movement is due to the ground accelerations and to the tank deformation that produce the fluid surface displacements and the convective pressure.

Many researchers consider the influence of the tank deformation on the sloshing to be negligible.

This is certainly true if only the deformation caused by the convective pressure is considered, in the hypothesis of tank deformability [5]. Seismic excitation was represented by an artificial time history compatible with the given free-field spectra applied at the base of the considered nuclear island.

In the application example only the horizontal translation direction is considered. The response of the structure was obtained for selected time steps of the input earthquake time history.

The seismic excitations were simulated by means of different artificial time histories in term of accelerations (run 2; run3; run 4; run 5), while in Figures 4 only the run 5 is represented, such as in a previous study (Forasassi, Aquaro, 2005), whose duration is equal to 12 seconds.

This one may simulate an extremely severe Earthquake (A_x = 1.26 g) which has not really probability of occurrence.

Before the development of the dynamic analysis, a modal analysis was carried out to evaluate the natural frequencies and modes of all the most relevant components of the considered system.

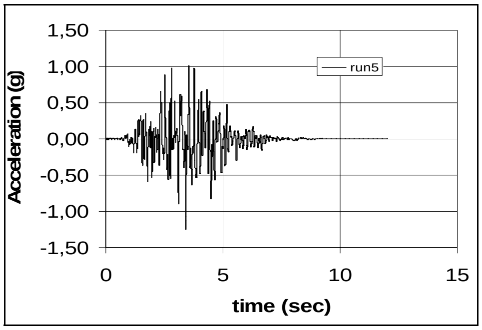


Figure 4 Seismic Acceleration Time Histories (ATH)- Case: run 5

NUMERICAL RESULTS

The structure models (Figure 5), described previously, as far as the seismic effect are here considered and implemented with MSC.MARC FEM Code, which allowed to assemble the mass, stiffness and to solve the equations of dynamic equilibrium at each point and time step, while the sloshing was simulated by means a commercial code dedicated to shock and impulsive phenomena (Dytran). This model simulates with Eulerian hexahedron elements the primary coolant and the cover gas, while the reactor vessel is simulated by means of Lagrangean shell elements. The coupling between the fluid and the structure was achieved with the algorithm called ALE (Arbitrary Lagrangean Eulerian coupling).

The ratio between the depth of the fluid (h=8.84 m) and the fluid free surface width (φ=5.92m) is equal to 1.49 and therefore far from the critical value 0.3374 (Faltinsen, 2001). Moreover the fluid oscillations will be reduced by the pressure of the cover gas and the presence of the inner vessel.

To help understand the nature of the internal oscillations induced by horizontal excitation in the internal-waves cases, an evaluation of the natural frequencies of the system has been carried out.

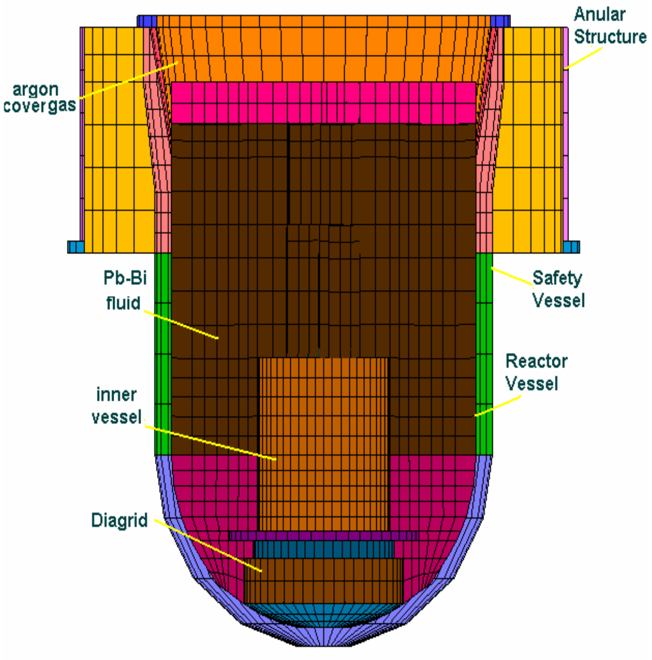
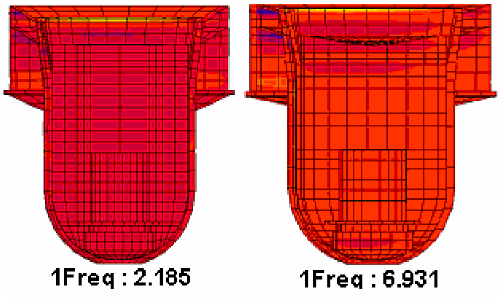


Figure 5 Whole Reactor fem model – Vertical Section

The calculated numerical frequencies (Figures 6 (a) and (b)) with and without heavy LBE, highlight that all the first whole reactor vessel frequencies are in the range of the acceleration amplification of the response spectrum and that there was a decrease passing from the first case to the second one because the lead bismuth eutectic density has a high value.

The carried out simulations may be conservative because not all the internal structures have been set up in this preliminary model. Therefore the fluid is assumed to cover a more extensive region inside the vessel and the obtained stresses might be greater than the real ones.



(a) (b)

Figures 6 Whole reactor natural frequencies with and without lead-bismuth eutectic

During an earthquake a measure of the sloshing intensity may be given by the fluid movement symmetry axis along the vessel.

The lead-bismuth free surface is generally characterized by a static pressure of 0.42 MPa, while at the vessel bottom the static pressure is equal to 1.34 MPa.

For instance in Figure 7 the maximum impulsive pressure, for the case of run 5 (extreme accident), is shown at the edge of the Diagrid component, while in the almost whole analyzed system the pressure changes cover an average range from 1 MPa to about 4 MPa. After occurrence of maximum impulsive pressure, the pressure does not increase even if the excitation continues (Figure 8). This may be due to the coolant free surface breaking wave motion that:

1) changes the effective mass of striking fluid;
2) decrease of elastic modulus due to the gas entrainment.

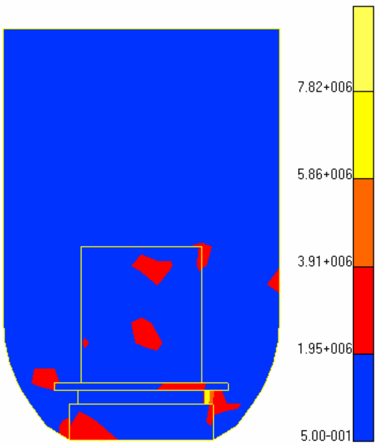


Figure 7 Maximum pressure behaviour in the fluid region

Similar remarks may be observed in all carried out analyses. The numerical results highlighted that the maximum impulsive pressure depends on the level of excitation and it does not necessarily occur at the level of the first effective wave [6].

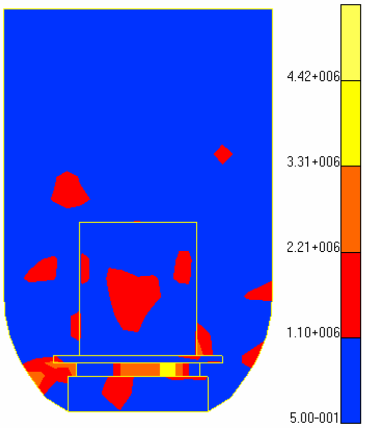


Figure 8 Pressure behaviour in the fluid region

In the studied case the response wave height become lower along with increase of internals components in the main reactor vessel. This means, as it might be found, that the presence of inner structures is favourable for stabilizing sloshing as showed in rather experimental data present in literature (Figure 9) [7].

Some other experimental data available in literature has been analyzed and used as reference for a following comparison with the carried out numerical results [8].

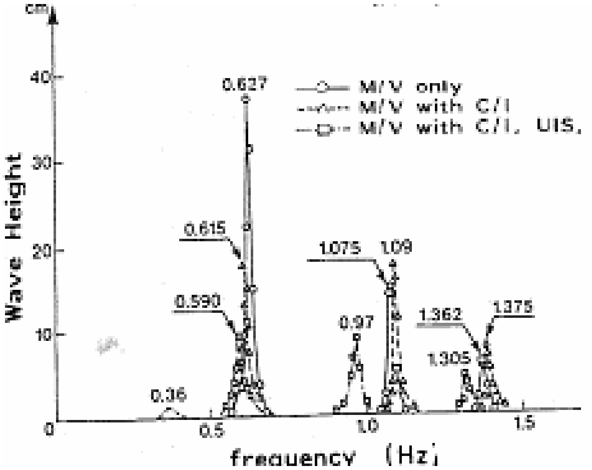


Figure 9 Horizontal experimental reactor vessel wave height

A preliminary assessment was done to verify that the similarity law follows to the reference scale factor 1/n. Therefore, the comparison between numerical results and experimental ones has showed a rather good agreement with the calculated wave eight variations as walls displacements variations along x direction versus time, for a representative vessel point (Figure 10).

The maximum stress (Figure 11) in the RV and SV has been also determined. In the analysed case this value is located at the bottom of the vessel and it is due to the pressure induced by the gas cover, the lead bismuth eutectic weight as well as to the vessel characteristics.

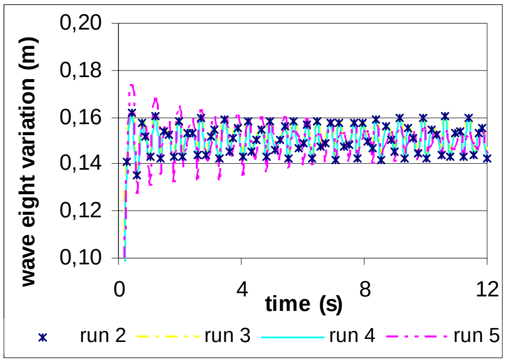


Figure 10 Reactor vessel displacement variations

Therefore the distribution of the Von Mises equivalent stress on the Reactor and Safety Vessel model that reaches in the first instant transient time the maximum value equal to 237 MPa.

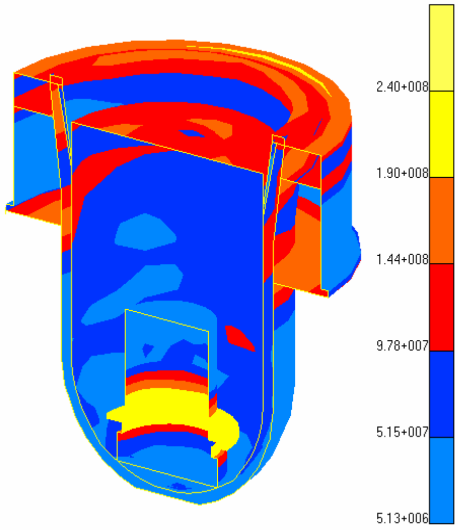


Figure 11 Maximum stress in the RV and SV (Case: run 5)

CONCLUSION

Analysis and design of the NPP structures involve considerations not only on the available geometry but also on the capacity of the most important structural members that transfer the seismic inertial loads from their application points to the internal structures.

On the base of very preliminary analyses, the effects of fluid–structure interactions effects for the considered XADS nuclear reactor as an example have been presented. The preliminary analyses performed show the importance of the interaction between the fluid and the reactor vessel both in terms of the level of stress as well as their distribution.

The model even if used to simulate the interaction considers only some internal components; it may be useful for an upgrading design of the reactor vessel. In general, the model analysis (considering the frequency dependency of the structural parameters) yielded that the sloshing motion itself may be very much amplified due to the flexibility of the wall tank.

The lead bismuth eutectic sloshing calculated is far from the critical values and the maximum displacement variation of fluid centroid in the direction of the excitation is about 10 mm (for the greatest amplitude excitation).

The obtained numerical results have been compared with some rather data available in literature, in order to verify the mentioned results and to assess the model reliability.

In the mentioned RV the point of the maximum Von Mises equivalent stress appears to be located at the vessel bottom. In the analysed example, considering the maximum acceleration excitation about 1 g (run 5), the obtained maximum equivalent stress at the vessel bottom is about 238 MPa, while at the top roof one is about 150 MPa.

From this study the following conclusions may be drawn:

- Fluid–structure interaction effects have been proved of meaningful importance in the dynamic behaviour of the reactor pressure vessel with heavy coolant fluid.

- As a result of heavy fluid effects, frequencies of the nuclear reactor are significantly lowered in presence of internal components.

- Damping factors of sloshing are not influenced by the wall stiffness but they are influenced by the presence of inner structures.

- In the studied case structural integrity of the internal structure against sloshing was confirmed.

The activities performed up to now have highlighted the need to improve the mechanical-structural design of primary system components, however with no significant modification of their functional geometry or their layout within the main vessel.

Furthermore it was confirmed, by comparing the experimental results, that the employed FEM analysis can simulate the seismic behaviour of reactor vessel with good accuracy and is applicable in a seismic design.

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