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NUMERICAL EVALUATION OF SLOSHING EFFECTS IN ELSY INNOVATIVE NUCLEAR REACTOR PRESSURE VESSELS SEISMIC RESPONSE

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ABSTRACT

In Europe a great effort has been made in the Lead-Bismuth Eutectic (LBE) technology, for use in the sub-critical reactors, and its natural development is represented by the use of pure lead that is less corrosive, chemically inert and in the foreseen environment has good neutronic and thermal-hydraulic characteristics, therefore it appears to be a suitable coolant for a fast reactor.

The main purpose of this study deals with the evaluation of the sloshing dynamic effects of lead coolant during a safety shut down earthquake applied to a conceptual Lead-cooled Fast Reactor (LFR) Generation IV (GEN IV) Nuclear Power Plant design, with reference to the ELSY project system configuration that is under development within the ongoing European 7FW ELSY Program.

ELSY is an innovative small size pool-type reactor (600 MWe) cooled by pure lead, characterized by a compact and simple integrated primary circuit; by the way this configuration is favourable from the point of view of the reduction of the seismic loads and of the negative effect of the high lead density. Therefore, the fluid-structure interaction problems and the free oscillations of the heavy metal primary coolant attracted the attention because during a strong motion earthquake the lead surrounding the internals may be accelerated and the so-called hydrodynamic interaction, due to the coolant sloshing, may significantly influence the stress level in the reactor pressure vessel (RPV).

To the purpose, the effect of the rigidity of adjacent internals walls and coupling between coolant and vessel are considered

An adequate numerical modelling, by means a 3-D finite element model, was set up and used for the foreseen structures dynamic analysis, due to the inability of linear theory to describe accurately the wave's motion accounting for the complex considered RPV geometrical aspect as well as the material nonlinearities. Numerical results are presented and discussed highlighting the importance of the fluid-structure interaction effects in terms of stress intensity as well as the capacity of internals and vessel walls to withstand wave's impact and prevent instabilities.

INTRODUCTION

Fluid-structure interaction problems have attracted a great deal of attention because of their wide range of applicability. Liquid storage tanks may be severely damaged during earthquakes. Such damage includes buckling of the tank walls, damage of the roof due to sloshing, failure of connections in piping due to large bending moments, etc., may yield unacceptable consequences in terms of hazardous events to the environment and the population or in terms of systems for power generation. 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 associated with the oscillatory phenomena of the containers filling levels.

The dynamic behaviour of numerous fluid storage tanks has been widely investigated. However, most of these studies have focused only on the ground level cylindrical tanks and few on the underground or elevated quotes ones, characterised by other geometries [1].

The analysis of the liquid sloshing effects 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 [2].

The intent of this paper is to provide some contributions to the development of a European Lead-cooled System, known as the ELSY project (CEE-7 Framework Project); that will constitute the reference system for the large lead-cooled reactor of GEN IV. 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, rather "violent" waves can form and impact into the tank walls.

In these cases sloshing loads may arise and be 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 predictions are made particularly difficult by the non-linear nature of the phenomenon and by the large number of parameters affecting it, such as the rather complex tank geometry, liquid-fill height, period and amplitude of excitation and position of the system rotation centre.

In this paper a preliminary analysis with focus on the seismic effects is intended to evaluate the influence of the dynamic loads on the ELSY next generation reactor (figure 1) internals structure, accounting for their contribution to the overall damping of the system.

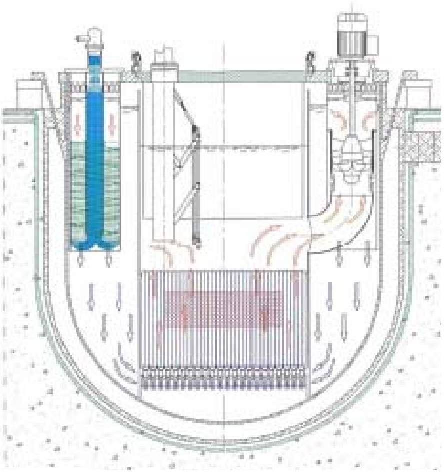


Figure 1 – Overview of ELSY initial preliminary scheme

STRUCTURE AND MODEL DESCRIPTION

New reactor designs should meet the criteria of sustainability (GEN-IV, 2002) and 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.

The ELSY general project objective aims to demonstrate the feasibility of a competitive and innovative safe lead-cooled fast reactor design based on simple technical engineered features. This general objective should be complemented by an analytical effort to assess the existing knowledge base in the field of lead-alloy coolants (i.e., lead-bismuth eutectic (LBE) and also lead/lithium) in order to extrapolate the already available knowledge base to pure lead, that achieves all of the GEN IV goals and gives better assurance of investment protection.

Preliminary designs of larger plants cooled by LBE have already been carried out in Korea and in Japan (with a power ranging up to 750 MWe). It is a natural development to select the use of pure lead as a coolant since it is chemically inert in comparison to sodium and is less corrosive, of lesser radiological concern when activated and cheaper than LBE. An efficient use of fissile fuel resources together with the ability to burn its own high-level wastes and also the ones coming from Light Water Reactors (LWRs) are primary design goals of several new reactor designs developed under the auspices of the Generation IV initiative [3].

ELSY reactor type in comparison with LWRs is characterized, from a mechanical point of view by the relevant fluid weight and by the reduction and simplification of the primary system. The pool-type, instead of the loop-type configuration, was chosen for the possibility to contain within the main vessel all the primary coolant components. An example of an improved scheme to be evaluated as a starting point for the ELSY primary system is the cylindrical inner vessel concept represented in figure 2.

The Reactor Vessel 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 Reactor Vessel (RV) has a fixed roof with an annular central part to accommodate the extension of cylindrical inner vessel and contains two water-air decay heat removal (WA-DHR) systems and also eight internal primary pumps coaxially assembled in the steam generators (SG) [4]. The steam generator (SG) and primary pump (PP) assemblies are an integral part of the primary loop immersed in the cold pool that is arranged in the annular space between the cylindrical inner vessel and the reactor vessel.

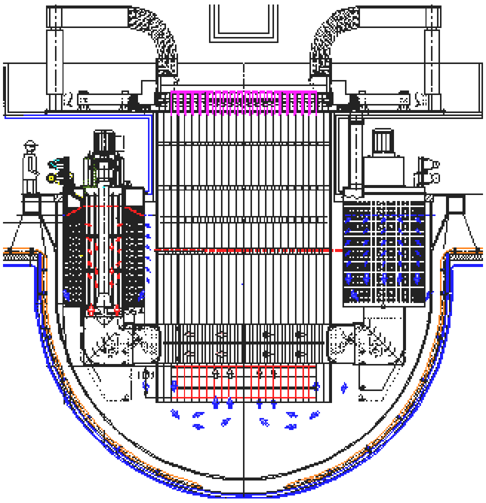


Figure 2 - Updated scheme of the ELSY Reactor

Moreover the RV is connected by means the mentioned "Y forged piece" at the Safety Vessel (SV), which is supported by and hangs from the Annular Boxed Structure (ABS), which is therefore the common support of both vessels. The upper part, already indicated as "Y forged piece", should transfer the whole weight of the RV/SV to the annular support and bear as well as sustain the Reactor Roof and the joined components. The Safety Vessel (SV) is made of a SS cylindrical shell and is characterized by an upper cylindrical and bottom hemispherical shapes.

The Reactor Roof ensures component support, reactor cover gas containment and the biological protection. Furthermore materials used in modelling ELSY nuclear reactor components are type 304L and 316L SS, while the choice of lead, as primary coolant, is motivated by good nuclear properties and thus, no intermediate coolant loop it is needed.

To the purpose of the assessment of the lead sloshing effects during an earthquake, in this preliminary study a system constituted by the following main and mutually interacting components was considered:

- the Safety Vessel with its annular box structure;
- the Reactor Vessel and its support system;
- the integral steam generator and pump assembly;
- the Water-Air Decay Heat Removal System;
- the inner cylindrical vessel;
- Molten primary coolant: pure Lead;
- Cover gas: argon

As for the numerical 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 reasonably limiting the considered details for calculation efficiency.

Modelling of 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 [5-6].

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 because it might produce stresses exceeding the allowable limits in localized parts of the reactor internals components. The fluid-structure interaction problems can be investigated by using different techniques such as added mass; Lagrangian-Eulerian approach in the finite element method (FEM) or by the analytical methods and related asymptotic solutions (e.g. Faltinsen).

Generally, the widely proposed procedures for the evaluation of the reactor vessel (or other conventional liquid retaining tank) response are based on linear liquid sloshing models [7].

The main goal of this study, however, is to estimate the overall effect of the interaction between sloshing and the wall motion; it is to be noted that in the present analysis not just the wall deformation due to sloshing itself but also that due to the action of the impulsive pressure is taken into account.

It must be pointed out that a realistic prediction of the considered phenomenon is 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 height, period and amplitude of excitation and position of the system centroid of rotation.

In the studied case, sloshing becomes a transient problem and its solution provides the fluid motion as well as the “time history” of hydrodynamic pressures and stresses on the reactor pressure and internals walls.

To the purpose the effect of the adjacent walls and coupling between internal primary coolant and vessel are considered.

As mentioned, results available in the literature indicate that sloshing motion has been investigated with either vertical or horizontal excitation.

The present paper investigates numerically free surface sloshing in externally excited RV with a focus on moving liquid tanks for horizontal excitation.

The cylindrical reactor vessel has walls characterised by an elastic perfectly plastic behaviour and a radius, a, and a mean liquid depth, H, as shown in figure 3.

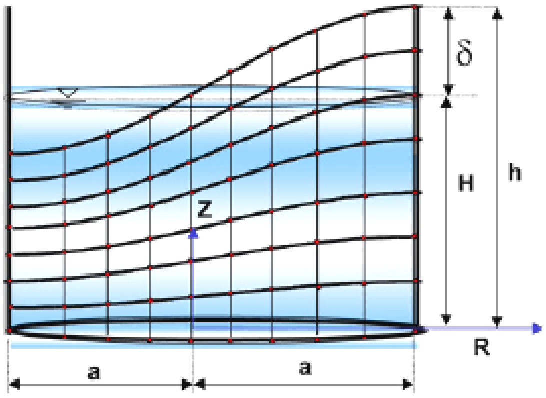


Figure 3 - Sloshing behaviour scheme

The considered tank contains an ideal fluid, assumed to be irrotational, not viscous and incompressible, that is subjected to horizontal seismic ground acceleration A_x.

The fluid flow is described through a velocity potential function satisfying the Laplace equation within the fluid, kinematic condition on the tank wall, and kinematic and dynamic free-surface conditions [8].

The equations of fluid motion of the system can be expressed in terms of cylindrical coordinates (R, θ, z) and velocity potential, Φ, as follow:

$$\nabla^2\Phi = 0 \quad \Rightarrow \quad \frac{1}{\mathrm{R}}\frac{\partial}{\partial R}\left(R\frac{\partial\varphi}{\partial R}\right)+\frac{1}{R^2}\frac{\partial^2\varphi}{\partial\theta^2}+\frac{\partial^2\varphi}{\partial z^2} \tag{1}$$

The kinematic condition on the free surface is:

$$\left|\frac{\partial h}{\partial t}=\frac{\partial\varphi}{\partial R}\frac{\partial h}{\partial R}+\frac{1}{R^2}\left[\frac{\partial\varphi}{\partial\vartheta}\frac{\partial h}{\partial\vartheta}\right]-\frac{\partial\varphi}{\partial z}=0\right|_{z=h} \tag{2}$$

$$\left|\frac{\partial\varphi}{\partial t}=-\frac{1}{2}\left[\left(\frac{\partial\varphi}{\partial R}\right)^2+\frac{1}{R^2}\left(\frac{\partial\varphi}{\partial\vartheta}\right)^2+\left(\frac{\partial\varphi}{\partial z}\right)^2\right]-g\delta-A_x x\right|_{z=h} \tag{3}$$

where h is the free surface elevation above the still liquid level, measured form the bottom of tank; g the acceleration of gravity, A_x the acceleration and t the time.

One of the main difficulties for determining the sloshing behaviour in a cylindrical vessel, when dealing with the numerical nonlinear solution of the hydrodynamic problem, is that the computational grid on the curved shape walls has to be modified at every time step as the free surface of the liquid changes with time (resulting in a high complex analytical solution of the free surface fluid motion).

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;
- Argon has ideal gas behaviour.

In order to better understand the response of the reactor vessel and the dynamic effects of the fluid and/on the internals, the seismic analysis of an application example was performed adopting an input motion with peak ground acceleration equal to 0.35 g, in the horizontal translation direction.

The seismic excitation was represented by means an artificial time history in term of accelerations (figure 4), compatible with the given free-field spectra applied at the ABS structure, assuming a rigid behaviour of the ELSY nuclear island and for a duration equal to 12 seconds.

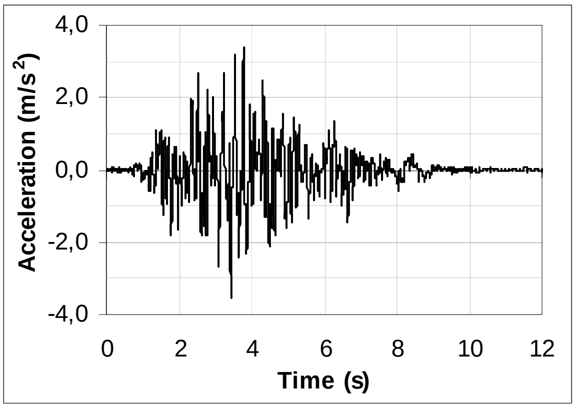
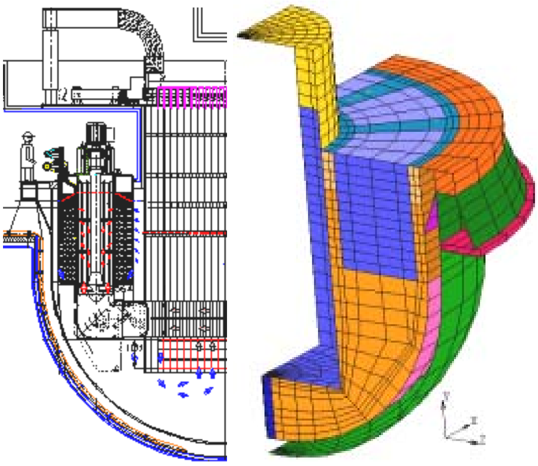
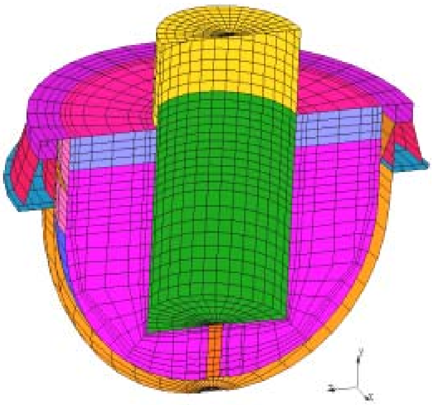


Figure 4 - Seismic Acceleration Time Histories (ATH)

Furthermore to achieve the mentioned purpose two model were set up, with and without internal structures, represented in figures 5 (a) and (b), both characterized by the same geometrical and material properties.



(a)



(b)

Figures 5 - ELSY Reference Assembly Scheme and FEM set up section models with (a) and without (b) internals

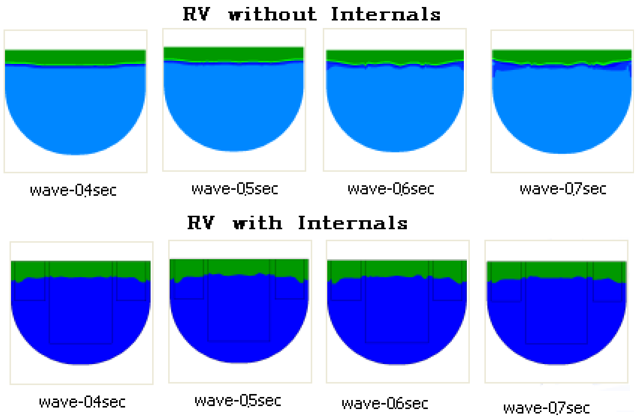
NUMERICAL RESULTS

As already mentioned, in this paper, non linear sloshing is studied for cylindrical tanks subjected to earthquake ground accelerations with models that include the main relevant internal components; hence it may be useful for an upgrading design and internals of the reactor vessel.

The previously described structures were implemented with dedicated finite element codes, which allowed to set up adequately the mentioned components and to solve the equations of fluid motion at each point and time step. In the codes, the fluid-structure interaction study was performed using a coupling algorithm, called ALE (Arbitrary Lagrangean Eulerian coupling), with interacting materials modelled in Eulerian and Lagrangian meshes. The interface surface serves as a boundary for the flowing Eulerian material during the analysis.

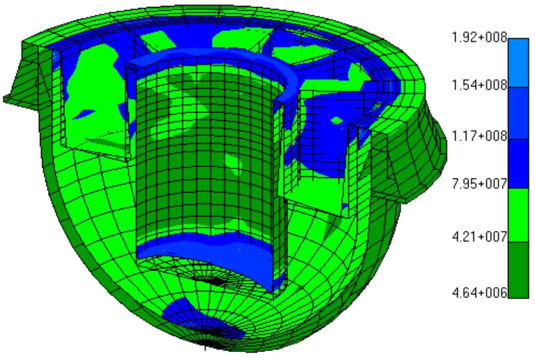
To the purpose Eulerian hexahedron elements were used to describe the primary coolant and the cover gas behaviour, while the reactor vessel and internals structures by means of Lagrangean shell elements. To help understand the nature and the effects of the fluid waves oscillations that might result in a rather large increase of stresses and pressure in the RV and internal components when a horizontal excitation is applied, an evaluation of the natural frequencies of the system has been carried out, highlighting that reactor vessel frequencies are in the range of the acceleration amplification of the considered earthquake response spectrum in the structure.

Sloshing analyses numerical results are presented in the following figures and discussed in order to highlight the importance of the fluid-structure interaction effects in terms of stress intensity of pressure distribution inside the RV and internal components as well as of the fluid movement along/inside the vessel. The inner structures seems to influence the fluid waves that otherwise could impact on the reactor roof, as showed in figures 6, that represents a comparison of the sloshing wave motion between the RV with and without internals. Moreover in the studied case the response wave height become lower along with the presence and dimensions of internals components in the main reactor vessel. Furthermore the impact and motion of liquid lead, during the seismic analysis determine an increase of pressure and stress on all reactor vessel and internals components.

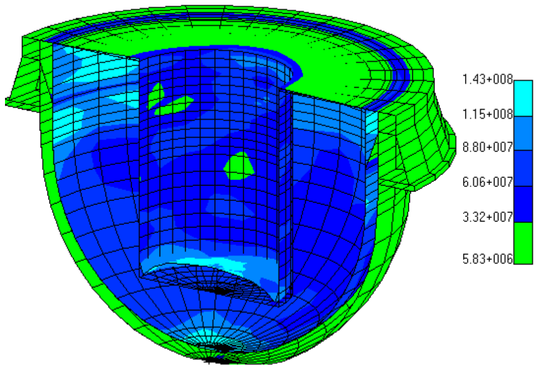


Figures 6 -Sloshing wave behaviour RV with and without internals comparison

Overviews of Von Mises stress intensity distribution in correspondence of the maximum acceleration value is represented in figures 7, as an example, for both cases considered in order to highlight the favourable and stabilizing effects of inner components (as it was possible to foresee).



(a)



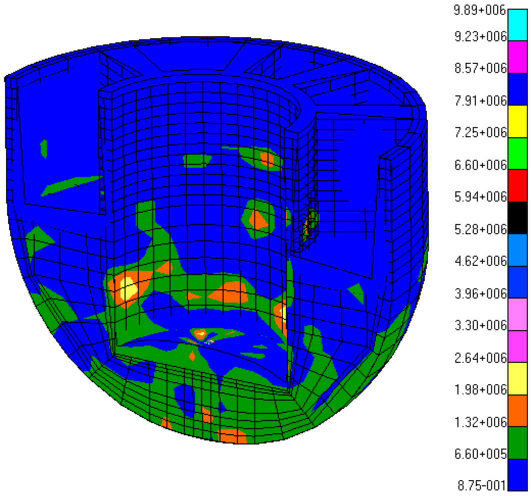
(b)

Figures 7 - Von Mises stress intensity distribution inside ELSY reactor vessel at the first sloshing wave

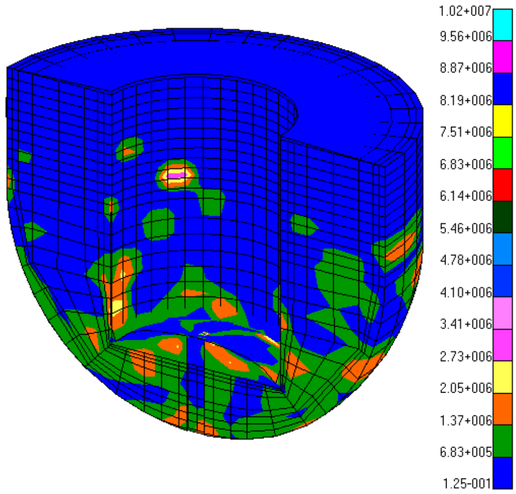
In the analysis the Von Mises stresses distribution values into the RV and SV resulted to be located at the bottom of the cylindrical inner vessel and at the roof and are determined by the sloshing pressure induced by the fluid surface movement, the lead weight as well as to the vessel characteristics, for both the analyzed models.

It is worthy to note that the Von Mises stress intensity values are greater in the first model (with internals). These values may be due to the walls deformation and to the different internals constraints that connect their upper part rigidly to the roof while allow free displacement at the bottom one. Moreover the obtained maximum pressure distributions for both models are represented in figures 8, highlighting that the liquid free surface pressure oscillates around the static value (about 1 MPa) with the maximum impulsive value at the bottom edge of the inner vessel component, while in the almost whole analyzed system the pressure variations cover an average range from 1 to about 2 MPa.

Furthermore after the occurrence of maximum impulsive value, the pressure does not increase further even if the excitation continues.



(a)



(b)

Figures 9 - Maximum pressure behaviour in the RV with (a) and without (b) internals

This favourable behaviour may be due to the mixing and entrainment of the cover gas into the lead that may result in a breaking wave motion and in a change of the effective mass of striking fluid as well as to the fluid movement, which results in a energy dissipation effect influencing the pressure behavior. The numerical results highlight 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 [9]. Furthermore it is worth to note that the increase of pressure is strictly dependent on the liquid surface displacement known as "convective pressure" as well as by the walls tank deformability (fluid pressure) [10].

Moreover, a coupling exists between the pressure components because the fluid surface displacement is determined by the ground acceleration and the wall deformation. Moreover the obtained inner structures displacements highlighted the presence of some criticality of internal structures that may be used to suggest further improvements and optimization of the reactor vessel internals design.

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

CONCLUSION

Analysis and design of the innovative liquid metal coolant NPP involve safety considerations not only on the available geometry but also on the capacity of the main relevant system and components to withstand the effects of transferred earthquake motion (seismic excitation) through the contained heavy liquid to the reactor vessel and its internals structures.

In the carried out preliminary analyses for the considered innovative nuclear reactor (ELSY) the effects of fluid-structure interactions have been presented, highlighting the importance of the coupling between the fluid and the reactor vessel internals both in terms of the stresses level and distribution.

A numerical approach is proposed for the solution of the nonlinear hydrodynamic problem of the reactor pressure vessel subjected to horizontal seismic ground accelerations.

The input acceleration may determine the arise of fluid sloshing waves that may induce relevant hydrodynamic pressures on the RV and internal components walls which in turn generates a corresponding stress intensity distribution.

The obtained numerical results, for models with and without the main internal structures, have been compared in order to verify and confirm the stabilizing effects of the considered inner components. In both analysed RV types, the maximum Von Mises equivalent stress values seem to be located at the bottom of the inner cylindrical vessel and on the roof. Furthermore the obtained internals maximum displacements, due to the fluid motion, are rather large and highlight a criticality in the reactor internals design, while the SV and RV ones are negligible.

The sloshing analyses 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. The fluid-structure interaction effects have been thus proved of meaningful importance in the dynamic behaviour of the reactor pressure vessel with heavy coolant fluid.

The set up model, even if used to simulate the fluid-structure interaction, includes some relevant internal components; nevertheless it may be useful to further upgrade the reactor vessel and internal design.

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