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Preliminary evaluation of the Fluid-Structure Interaction effects in a LFR

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CONTENTS

INTRODUCTION

Nuclear plants should be designed to be highly secure and capable to withstand a wide range of internal and external extreme accident loads, such as earthquakes, tsunamis, etc., whose intensity exceed the design level one.

Fukushima Dai-ichi NPP

After Fukushima accident, the question is: NPP response in beyond design earthquake conditions is yet acceptable ??

The seismic behaviour of a Liquid Metal Reactor is of meaningful importance because the reactor behaviour is influenced by the fluid-structure interaction and sloshing phenomenon (liquid waves can form and impact on RV and internals walls).

FLUID-STRUCTURE INTERACTION

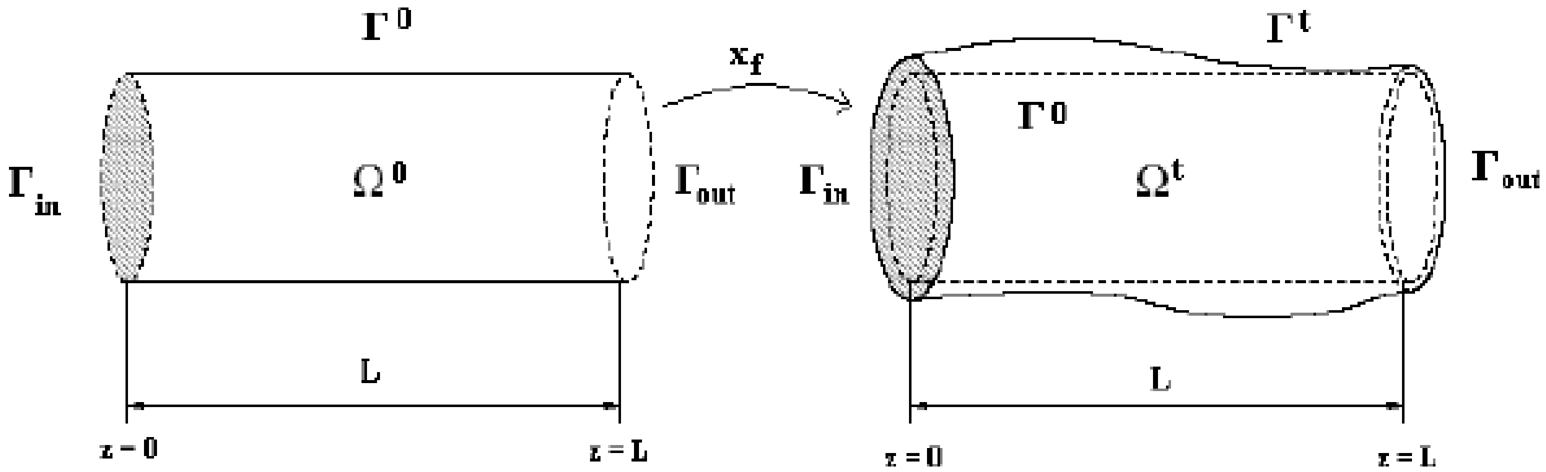
Fluid-structure interaction (FSI) problems have attracted a great deal of attention because of their wide range of applicability. Numerous physical phenomena may arise and characterize the free liquid surface (sloshing phenomenon) depending on the type of the external excitation, the shape and modal behaviour of the container, the filling depth of the liquid , etc.

The basic problem of fluid-structure interaction involves the evaluation of the hydrodynamic pressure distribution, forces, moments and natural frequencies of the free-liquid surface.

In LFR, the inertia forces of the coolant may significantly increase during the seismic motion and result in a hydrodynamic pressure acting on the reactor vessel and its internals walls causing possibly the dynamic buckling, the over stressing of component, etc.

FSI ANALITYCAL APPROACH

The fundamental theory of liquid surface waves is documented in several references (see, e.g., Lamb, 1945, Stoker, 1957, Brodkey, 1967 and Barber and Ghey, 1969, Faltinsen 2000, etc.). In the analytical approach the fluid behaviour is analyzed assuming the fluid as incompressible and Newtonian, characterized at time t by a deformable domain Ω^0. The motion effects determines an evolution of the domain Ω^t, not known a priori.



The new profile Γ^t (representing the liquid free surface motion induced by the FSI), from a mathematical point of view, is extremely complex and involves the speed and the pressure of the fluid, the displacement of the structure and the position of points in the domain Ω^t at each instant t.

FSI ANALITYCAL APPROACH

The widely used analytical approach is based on the classical equations governing the free motion of the fluid in terms of potential theory (potential flow theory with approximate asymptotic or modal solution).
The fluid motion in a partially filled and rigid tank (in cylindrical coordinates (R, θ, z) and velocity potential, Φ) assuming the liquid incompressible, not viscous and irrotational, is calculated :

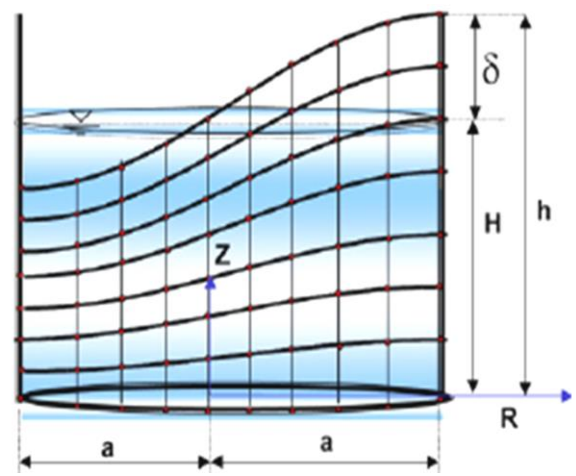
$$\nabla^2\Phi = 0 \quad \Rightarrow \quad \frac{1}{R}\frac{\partial}{\partial R}\left(R\frac{\partial \varphi}{\partial R}\right) + \frac{1}{R^2}\frac{\partial^2 \varphi}{\partial \theta^2} + \frac{\partial^2 \varphi}{\partial z^2}$$

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

kinematic condition on the free surface

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

dynamic condition on the free surface

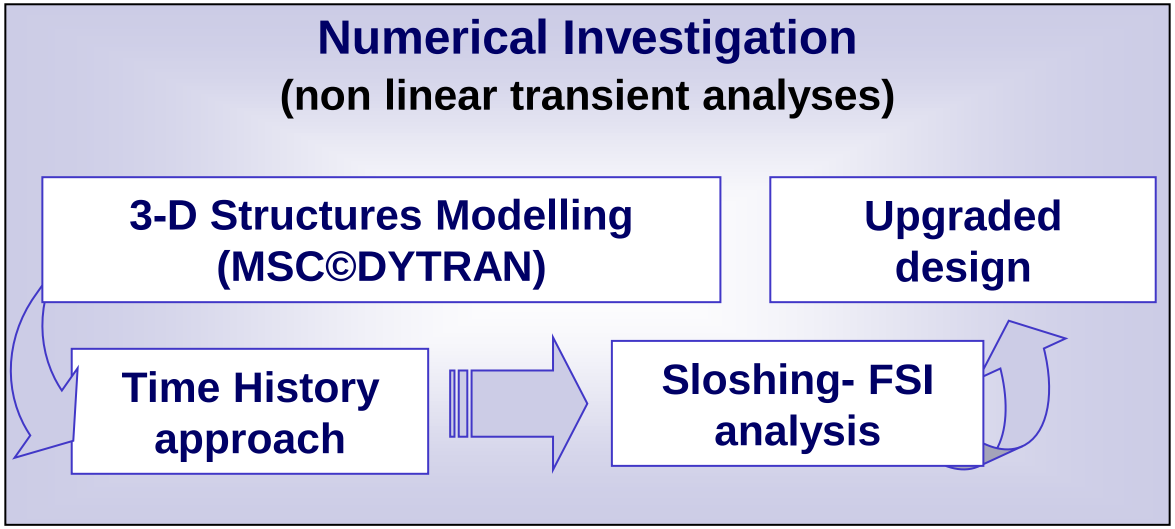


h is the free surface elevation; g the acceleration of gravity, A_x the acceleration and t the time.

Since the realistic prediction of the sloshing is made particularly difficult by the non-linear nature of the phenomenon (caused by the tank geometry, liquid height, etc.) a numerical approach is necessary.

FSI NUMERICAL APPROACH

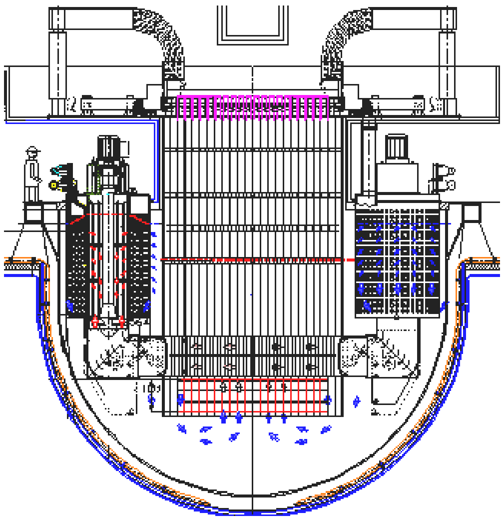
The FSI problem may be investigated with dynamic FE codes. The procedure adopted to evaluate the structural performance of ELSY reactor in BDBE conditions, is based on Time History and Substructure approaches along with the implementation of rather complex FE models.



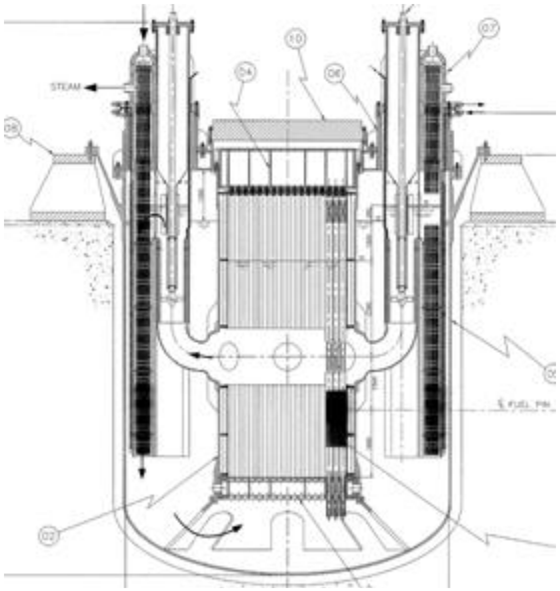
The solution of sloshing phenomenon will allow to determine the fluid motion, the hydrodynamic pressures and stresses of the RV and internals structures.

DESCRIPTION OF LFR

A lead cooled reactor (promises to readily meet the Gen IV goals), has been considered for the aim of this study: Particularly ELSY system, whose evolution is represented by the ALFRED reactor, was investigated.



ELSY configuration (6FP)



ALFRED configuration (7FP)

The RV has an integral shape ("pool type"), housing all the primary system components (SGs, PPs, core, DHRs, etc.). The "Y" junction allows to discharge the whole weight of reactor on the reactor building through the SV anchorages.

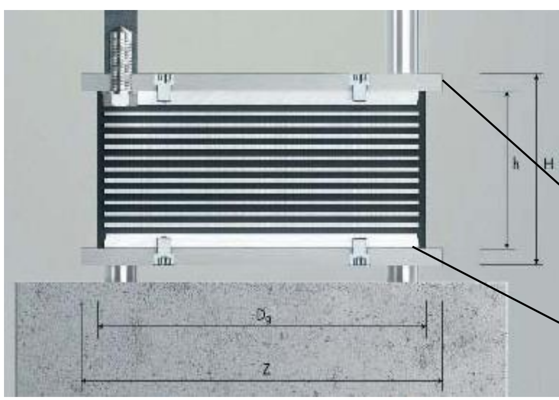
DESCRIPTION OF LFR RB

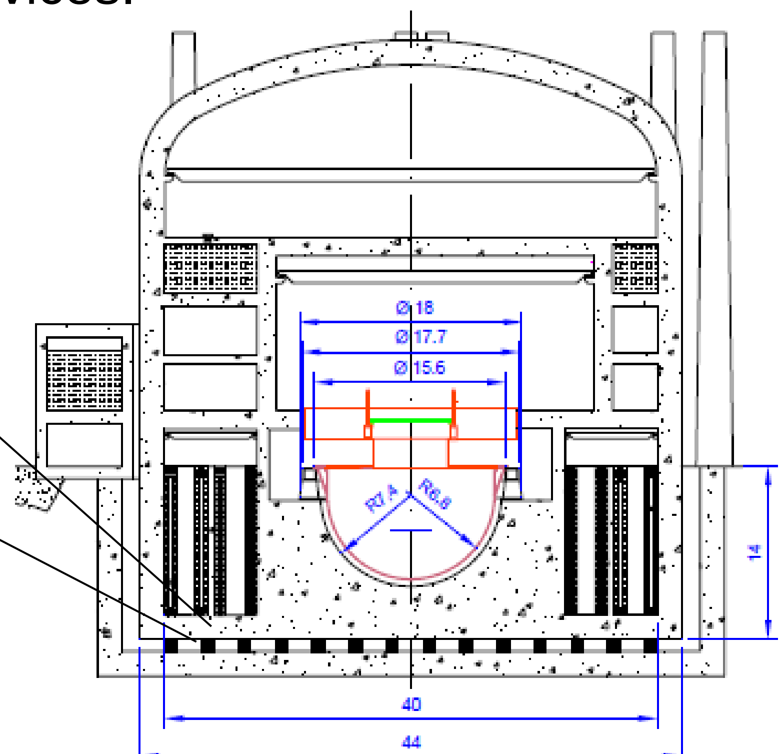
The reactor building (RB) configuration was the same proposed in the ELSY project and developed by EA.

The RB has 44 m external diameter and about 48 m height.

The reason for a building so large in diameter is related to the need to accommodate a large RV, about 18 m diameter, the decay heat removal system pools, the refueling devices, etc.

HDRBs were assumed as isolation devices.





APPROACH TO SEISMIC ANALYSIS

Modeling Hypotheses

The modelled structures are:

- the Reactor Building;
- the Safety Vessel and Reactor Vessel;
- the primary coolant: pure lead;
- the cover gas.

Lead

Pure lead is modelled as linear elastic and isotropic behaviour;

Fluid and structure exchange mechanical energy along their interface.

The FSI are simulated through the Lagrangian Eulerian (ALE) algorithm.

SSCs

RV, SV and Internal structures are assumed to have elastic-plastic behaviours.

Cover gas

Argon behaviour is modelled adopting the law of perfect gas.

APPROACH TO SEISMIC ANALYSIS

Main points to be implemented in the non linear analysis:

1. Characterize Beyond Design Basis Earthquake (BDBE) by time histories (ATH) or response spectra according to the analysis type

2. Models and simulation methodologies

3. Seismic Analysis of the isolated NPP

4. Development of Floor Response Spectra (FRS) or Time Histories

5. Identification of main parameters influencing the plant response, by collecting and analyzing the obtained results

6. Setting up of sub-structure models to analyze the Fluid-Structure Interaction and sloshing phenomenon

7. Verification of Components behavior against BDBE

APPROACH TO SEISMIC ANALYSIS

Assumption for Isolation System:

1. **Isolators represented through an iso-elastic approach by means of springs coupled to dashpots.**

2. **Characterize HDRB (rubber type material having high damping properties and shear modulus (G) from 0.8 to 1.4 MPa).**

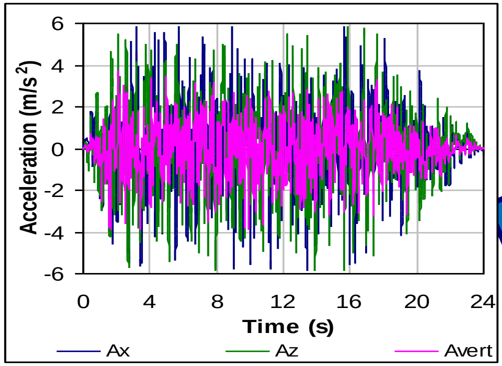
3. **Low natural frequency along the horizontal direction (f_i = 0.5 Hz).**

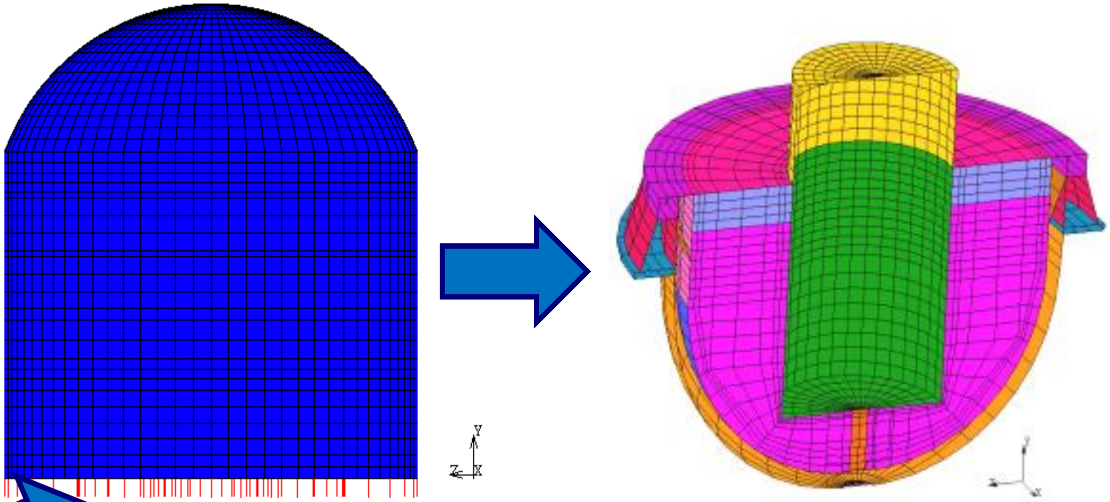
Accordingly to the ASCE 43-05, the isolation devices shall not suffer damage under BDBE condition and sustain the gravity and earthquake induced loads at 90th percentile lateral displacements consistent with 150% design level ground motion.

NUMERICAL ANALYSIS

The analysis was carried out in two step: the first one aimed at the evaluation of the propagation of the seismic accelerations through the isolated reactor building; the second one allowed to analyse the FSI effects induced by the fluid motion (seismically induced) in the RV and its main internal components.

Input Acceleration Time Histories



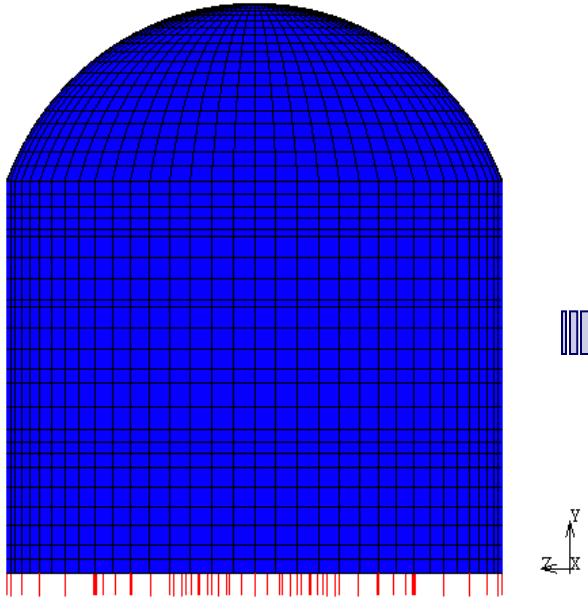


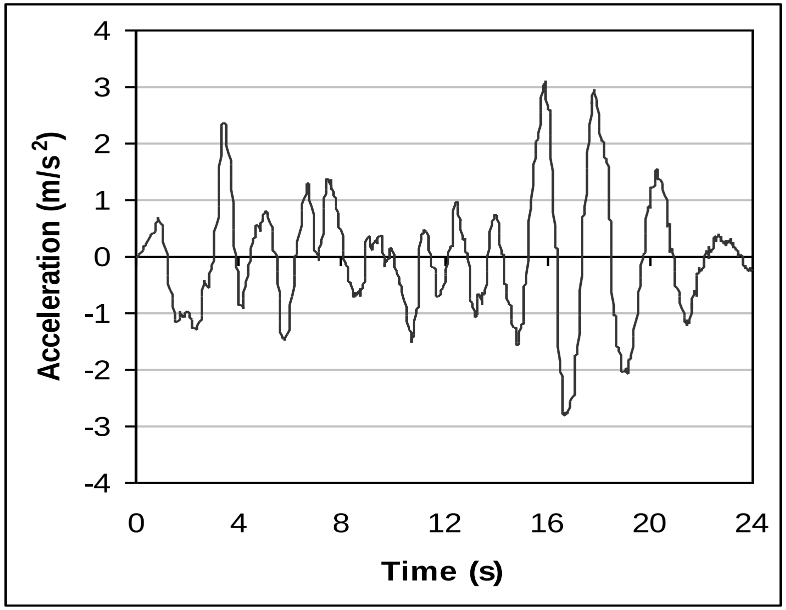
Reactor Building and RV preliminary models

The input acceleration data were elaborated according to the updated R. G. US NRC 1.60 and 1.92, considering a 5% of critical damping value.

RESULTS AND DISCUSSION

The analysis of the propagated accelerations confirmed the foreseen favourable effects of the isolation system in mitigating the horizontal components of the acceleration in the RB structure: the reduction with respect to the input accelerations was about 40%. The vertical component, instead, increases along the RB height.



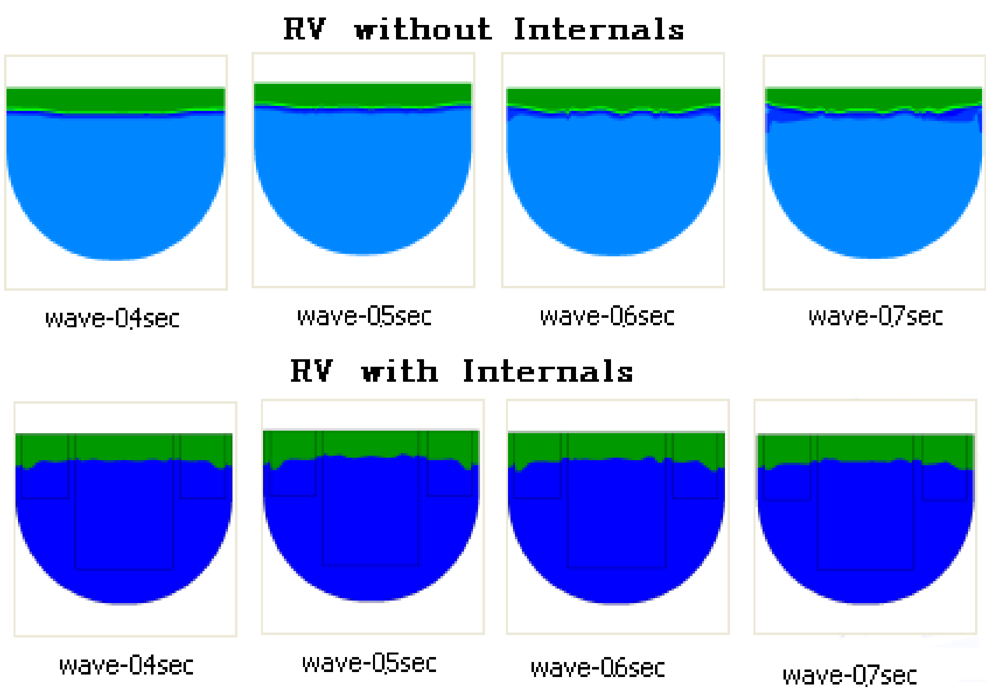


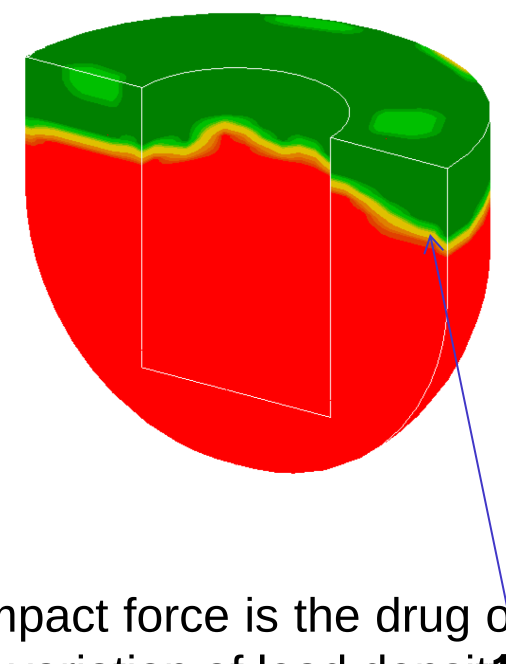
Horizontal acceleration at the SV anchorage

RESULTS AND DISCUSSION

The results in terms of the sloshing phenomenon (free surfaces motion) show the developments of wave at different times in the longitudinal direction. The presence of inner structures, fragmentising the fluid waves, reduce the risk of the impact of the lead waves on RV structures.

The elevation of waves, about 10 cm, resulted not sufficient to impact the roof.

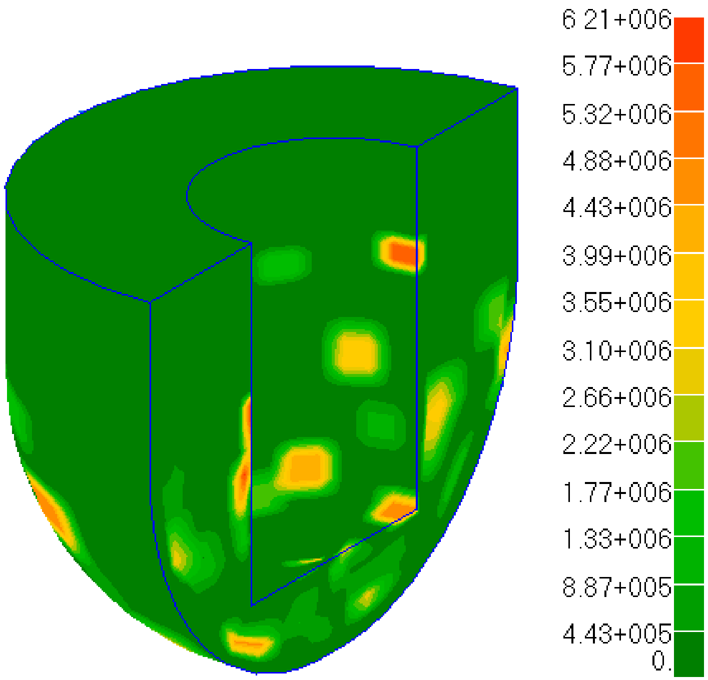




Another aspect that determine a further reduction of the impact force is the drug of the argon gas into the lead during the fluid motion causing the variation of lead density.

RESULTS AND DISCUSSION

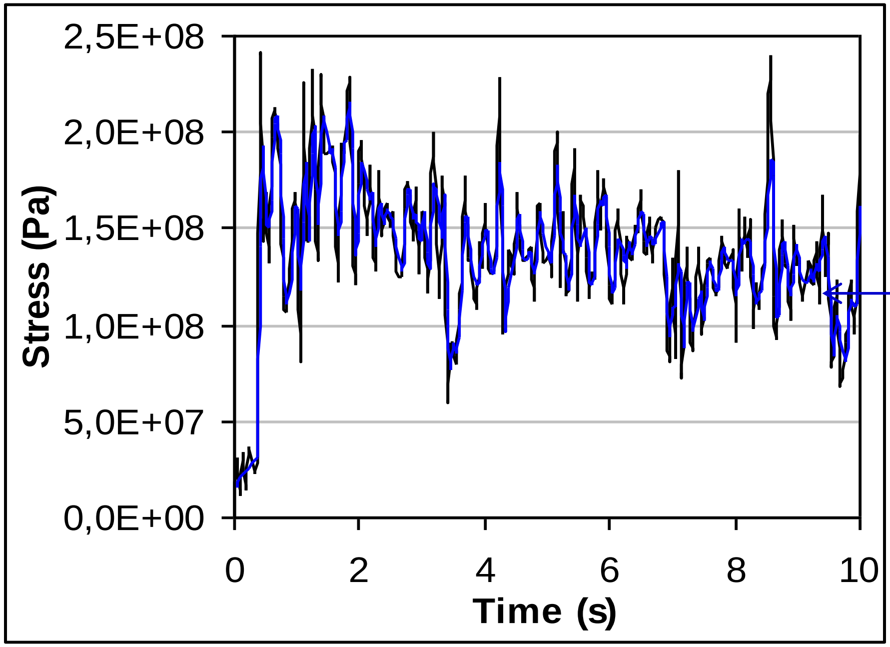
The hydrodynamic pressure has a mean pressure values ranging from about 1 to 2.5 MPa: values depending on the level of seismic motion intensity. Moreover the maximum pressure value (about 6 MPa at t ≈ 4 s) occurred on the bottom of the reactor vessel and of the inner vessel.



Although this high value, the seismic buckling of the internals is prevented, because the seismic pressure greatly increases as the coolant depth becomes deeper.

RESULTS AND DISCUSSION

The progressive lead motion, with the formation and impact of lead waves, seemed to determine high Von Mises stress values in RV, specifically, in the inner cylindrical vessel (about 210 MPa).

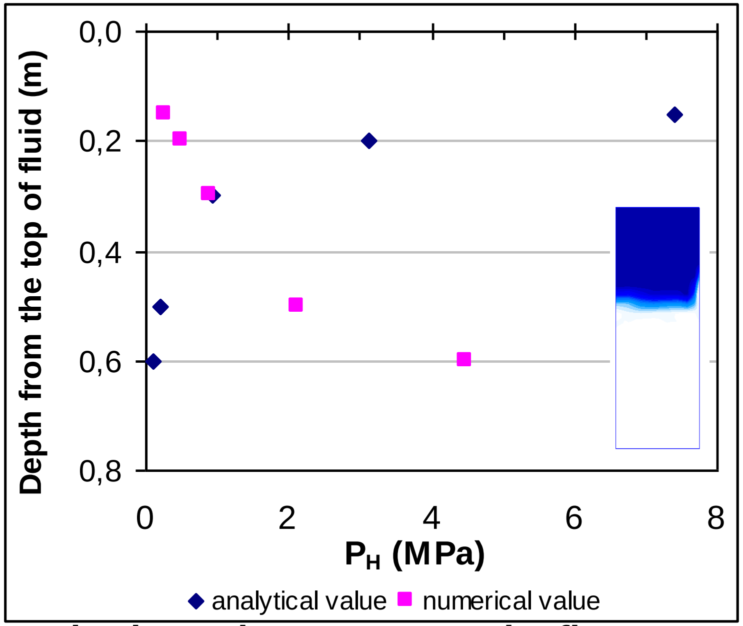


The smoothed behaviour does not contain the vibration component.

The calculated stress values, induced by the fluid motion and/or wave impact force, resulted not sufficient to determine the plasticization of the internals wall thickness and thus to impair their structural integrity in view of the ASME rules.

VALIDATION ANALYSIS

A comparison between numerical and theoretical pressure values (according to Eqs.C3.5-6 and C3.5-11 of ASCE 7-94 rules), was done.
The theoretical results underestimate a lot the pressure at the bottom of tank while overestimate them at the top free surface.



Hydrodynamic pressure at the first wave.

This discrepancy, compared to the numerical values, seemed due to the influence of the fluid buoyancy and waves formation, impact, fragmentation, draw back etc., not considered in the theoretical approach. However, generally, the discrepancy between the mean values of pressure resulted about 30%.

SUMMARY

- Conservative analyses were carried out since the fluid is assumed to fill a larger volume inside the vessel;
- LFR RV internals seemed particularly sensitive to seismic events due to the large mass of the coolant (inertia forces);
- Propagated horizontal accelerations in RB were reduced of about 40 %;
- Maximum Von Mises stresses resulted located at the bottom of the ICV;
- Deformations of the SV and RV are negligible while seemed quite large in internals: this is a criticality to be considered in the design of internals; they;
- The validation analysis highlighted the inadequacy of ASCE rules to predict hydrodynamic pressure; the discrepancy between the pressure mean values resulted about 30%.
- Future further developments are necessary to deeply evaluate the influence of isolators, considering an isolation frequency not far from the fundamental one of the fluid and/or of the soil.

Thanks for your attention