5. BDBE analysis results and discussion

Before the evaluation of the effects due to the dynamic forces exerted/induced by the fluid motion coupled to the FSI on to the RV structures, the influence of the dynamic loads propagating through the isolated reactor building was carried out.
Preliminarily a modal analysis was performed to check the consistency between the isolated RB structure and the isolation system and confirm that the considered RB structure behave as a "rigid body". Subsequently suitable seismic transient non linear analyses were carried out in order to calculate the acceleration values propagated up to the anchorage of the safety vessel.
Overviews of the obtained acceleration values allowed also to confirm the favourable effects of the isolation system in mitigating the propagation of the accelerations inside and along the RB containment structure (Fig. 11): reduction of about 40-50%.

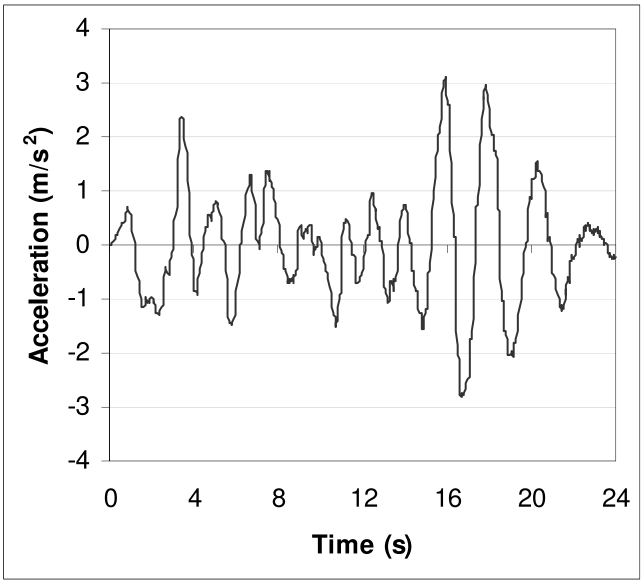

Figure 11 - Horizontal acceleration at the SV anchorage

It is important to highlight that due to the reactor vessel height (may be considered as an "elevated structure") and the large mass of the lead inside the reactor vessel, the sloshing phenomenon may become very important because it might produce stresses exceeding the allowable limits in localized parts of the reactor internals components and, therefore, locally impair their integrity.

In the performed analyses, only the transmitted horizontal acceleration was used as input in the RV substructure (previous shown in Figure 8 b) in order to analyze the structural effects induced by the ground motion on the RV and its main internal components, taking into account the effects of the moving lead.
The main assumptions made were:

- Fluid has an elastic, linear, isotropic behaviour;
- Lead is modelled as Eulerian fluid
- RV, SV and internal structures behaviour was linear elastic perfectly plastic as well as isotropic;
- Fluid and structure may exchange mechanical energy at the fluid-structure interface;
- The fluid-structure coupling is treated using the Arbitrary Lagrangean Eulerian;
- Argon is modelled as an ideal gas;
- BDBE input motion was represented through the horizontal velocity (along the x axis direction) applied at the SV.

The coupling effects between the fluid and the surrounding structures was calculated by means of the Arbitrary Lagrangean Eulerian coupling algorithm.
This algorithm allows to define an interface surface, that also serves as a boundary for the flowing Eulerian material during the analysis. Moreover, as already mentioned, the carried out simulations may be considered rather conservative because in the performed analyses the RV model did not include all internals structures and components, therefore the obtained results refer to a more conservative evaluation of the fluid-structure interaction between the reactor vessel and lead coolant and sloshing effects.
The preliminary results (structural effects and consequences) obtained from the carried out seismic analyses, are presented in the following figures and discussed in order to highlight the importance of the fluid-structure interaction phenomenon in terms of stress intensity distribution inside the RV and internal components as well as of the fluid movement along/inside the vessel (due to the impulsive and convective-sloshing components of the fluid motion).
It was observed that the elevation of waves, about 10 cm was not sufficient to impact the roof.

Lead motion coupled to the propagation of seismic wave resulted in a stress intensity distribution that could impair the structures capability to withstand the related dynamic loads on the RV and internal components. Moreover it was observed that the inner cylindrical vessel (which allows to enclose and sustain the core) structure seemed to influence the fluid waves motion by fragmenting the fluid wave.

The fragmentation allowed also to avoid that a more extensive lead mass could impact the roof: subsequently the impact force is reduced as well as the risk of structural damage.

Another aspect that determined a further reduction of the impact force is the drug of the argon gas into the lead during the fluid motion due to the resulted variation of lead density (at 6 s, as an example), clearly visible in Figure 12 around the yellow interface.

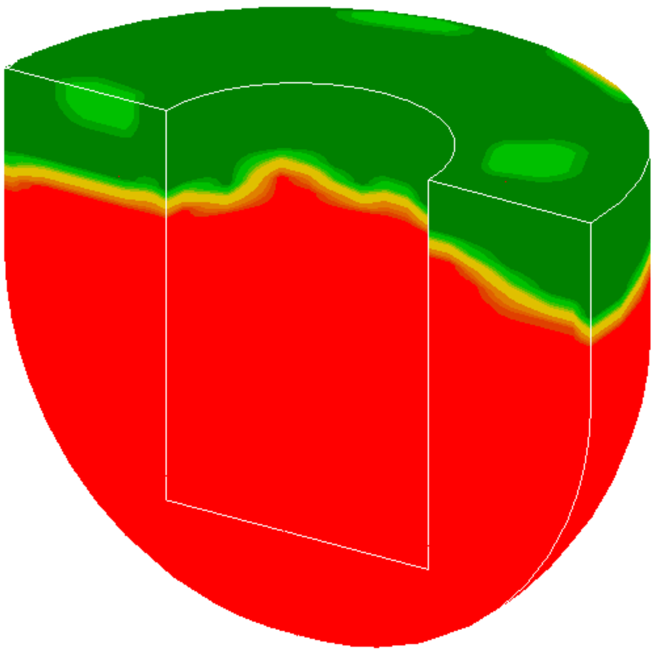

Figure 12 - Lead density variation behavior

Figure 13 shows the hydrodynamic pressure distribution into the reactor vessel due to the lead motion; it highlights that the mean pressure values range from about 1 to 2.5 MPa: this variation seemed to depend on the level of seismic motion intensity.

Moreover the maximum pressure value (about 6 MPa at $t \approx 4$ s) occurred on the bottom of the reactor vessel and of the inner vessel. Although this high value, the seismic buckling of the reactor vessel and its internals is prevented, for the reason that the seismic pressure greatly increases as the coolant depth becomes deeper.

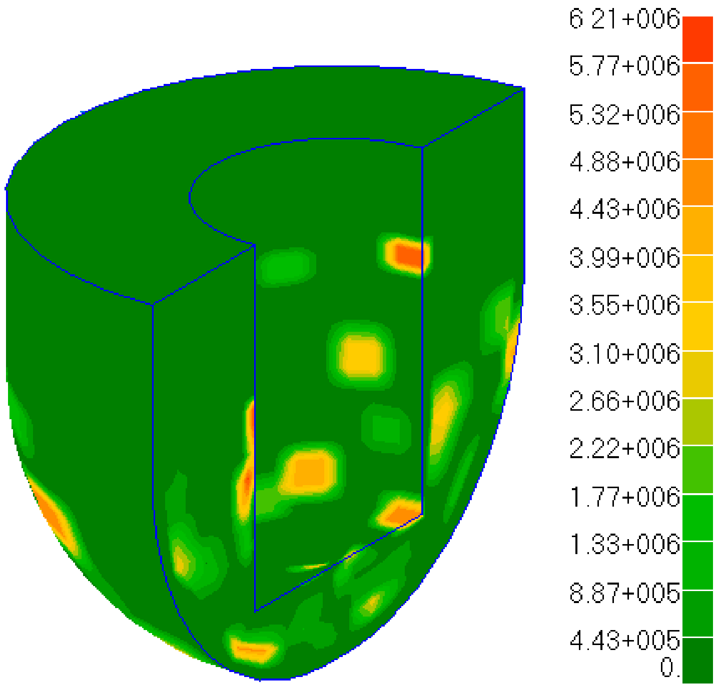

Figure 13 - Pressure distribution inside the RV at t ≈ 4 s

The progressive lead motion and, in particular, the formation and impact of lead waves (hydrodynamic pressure and the fluid movement characteristics) seemed to determine high Von Mises stress values (Fig. 14) in the reactor vessel and its internals walls.

The maximum stress values resulted about 210 MPa and localized in correspondence of the inner cylindrical vessel walls. Moreover in Figure 15 it is represented the calculated and smoothed behaviour of Von Mises stress; this latter is much more important from a structural point of view because does not contain the vibration component.

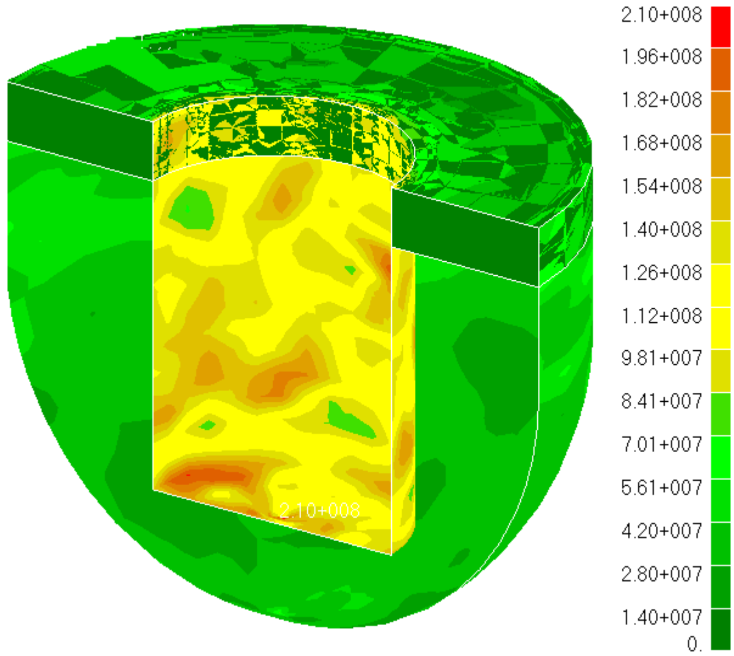

Figure 14 - Von Mises stress distribution inside RV

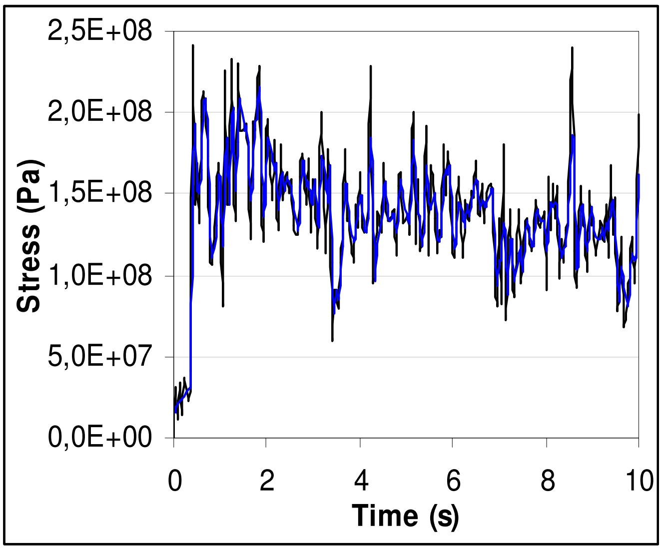

Figure 15 - Von Mises stress behaviour at the inner vessel wall

It is important also to note that the stress values calculated at the inner vessel wall, probably induced by the fluid movement and/or fluid wave impact on the RV structures, were anyway not sufficient to determine the plasticization of the RV and inner vessel wall thickness and therefore to impair their structural integrity in view of the ASME code rules.

In addition it is important to consider that in the performed analyses the fluid is assumed to fill a rather more extensive region inside the vessel, therefore the obtained stresses might be greater than the real ones.

6. Conclusion

In this report the results of preliminary seismic analyses are discussed, as obtained using the Time History method coupled to the substructure approach that allowed to study separately a hypothetical ELSY containment building and the reactor vessel with the inner cylindrical vessel.
To perform the analyses, appropriate Substructure approach with 3-D FEM models, representative of the isolated reactor building and of the safety and reactor vessels, etc., were set up in order to evaluate the seismic response of the structures and internal components that are particularly sensitive to the seismic events due to the large coolant mass in LFR.
In the carried out preliminary analyses, the effects of the coupling between the fluid and the reactor vessel structure both in terms of the stresses level and distribution were presented.
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, generate a corresponding stress intensity distribution.
The obtained preliminary numerical results, for implemented models, highlighted that:

1) the maximum Von Mises stress values seem to be located at the bottom of the inner cylindrical vessel;
2) the obtained RV internal displacements, due to the deformation induced by the fluid motion, are rather large and highlight a criticality in the reactor internals design, while the displacement of the SV and RV ones are negligible;
3) The sloshing analyses performed up to now have highlighted the need to improve the structural design of primary system components, however with no significant modification of their functional geometry or layout within the main vessel;
4) 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.
Finally it is important to note that future further developments should be necessary to evaluate more in depth the influence of isolators (considering also frequency not far from the liquid one in

order to evaluate the effects of possible isolators- FSI coupling) as well as that one of the soil-structure interaction, that at this preliminary stage was not considered.

7. References

1. IAEA, "Fundamental Safety Principles", IAEA Safety Standards Series No. SF-1, IAEA, Vienna (2006).
2. O.M. Faltinsen, "A nonlinear theory of sloshing in rectangular tanks", J. Ship Res. 18 (4) (1974) 224–241.
3. O.M. Faltinsen, O.F. Rognebakke, I.A. Lukovsky, A.N. Timokha, "Multidimensional modal analysis of nonlinear sloshing in a rectangular tank with finite water depth", J. Fluid Mech. 407 (2000) 201–234.
4. O.M. Faltinsen, O.F. Rognebakke, A.N. Timokha, "Resonant three-dimensional nonlinear sloshing in a square-base basin", J. Fluid Mech. 487 (2003) 1-42.
5. J. B. Frandsen, "Sloshing motions in excited tanks", Journal of Computational Physics 196 (2004) 53–87.
6. Standards ASCE 4-98, "Seismic Analysis of Safety-Related Nuclear Structures", ASCE, 2000.
7. F. Axisa, J. Antunes, "Modelling of Mechanical Systems: Fluid-Structure Interaction", Butterworth-Heinemann editor, 2009.
8. H Hernandez-Barrios et al., "Nonlinear sloshing response of cylindrical tanks subjected to earthquake ground motion"; Engineering Structures 29, 3364–3376, 2007.
9. R. A. Ibrahim, "Liquid Sloshing Dynamics", Cambridge University Press, 2005.
10. Mansani L.,"System Configuration for LFR", *International Workshop on LMFRs, Aix-En Provence, October 4-7, 2011.*
11. Cinotti L., Smith C. F., Sienicki J. J., Ait Abderrahim H., et al., "The potential of the LFR and the ELSY Project", RGN, n° 4, Juillet-Aout 2007.
12. Cinotti L., Smith Craig F., Sekimoto H., "Lead-cooled Fast Reactor (LFR) Overview and perspectives", Proceedings of the GIF Symposium 2009, Paris, France Sept. 9-10, 2009.
13. Alemberti A., Carlsson J., et. al. "European lead fast reactor – ELSY", Nuclear engineering and design, vol. 241, 2011, 3470-3480.
14. Mourogov V., Juhn P. E., Kupitz J., Rineiskii A. "Liquid-metal-cooled-fast reactor (LMFR) development and IAEA activities". *Energy*, vol. 23, Issues 7-8, 1998, 637-648.
15. NEA\AEN, "Handbook on Lead-bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-hydraulics and Technologies", *OECD Publications*, 2007.

8. Curricula of the research group members

The research group of the CIRTEN-University of Pisa is led by Prof. G. Forasassi and consists of: Dr. R. Lo Frano.

The prof. G. Forasassi is full professor of Nuclear Plants, of Structural and Mechanical Engineering Design and of Design of Complex Plant.

The research activity is documented in over 150 publications (http://arp.unipi.it/listedoc.php?lista=ALL&ide=1190&ord=C) focused in particular on the study of the safety and design of components of complex systems and nuclear, the safe transport and storage of radioactive materials etc.

The prof. Forasassi, former Director of the Pisa University and Vice-Chairman DIMNP-AIN, is currently President of the National Consortium CIRTEN (Interuniversity Consortium for Nuclear Technological Research) which is participated by the University of Pisa since its foundation in 1994, together with the Polytechnic of Milan and Turin and the University of Padova, Palermo and Rome 1-La Sapienza and since 2010 by the University of Bologna.

- Dr. Rosa Lo Frano is junior researcher at the University of Pisa.

Since 2007 he has been/is assistant-professor courses: Techniques of construction machinery, chemical and nuclear design of the plant complex. The research activity concerning the study of security issues and design of nuclear facilities, the safe transport and storage of radioactive materials, is documented by more than 50 publications in international journals and conference proceedings of the field (http:// arp.unipi.it / listedoc.php? list = ALL & ide = 11443 & ord = C).