Risk of Sloshing in the Primary System of a Lead-Cooled Fast Reactor

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Abstract: Pool-type designs of Lead-cooled Fast Reactor (LFR) aim for commercial viability by simplified engineering solutions and passive safety systems. However, such designs carry the risks related to heavy coolant sloshing in case of seismic event. Sloshing can cause (i) structural damage due to fluid-structure interaction (FSI) and (ii) core damage due to void induced reactivity insertion or due to local heat transfer deterioration. The main goal of this study is to identify the domain of seismic excitation characteristics at the reactor vessel level that can lead to exceedance of the safety limits for structural integrity and core damage. Reference pool-type LFR design used in this study is the European Lead-cooled SYstem (ELSY). Liquid lead sloshing is analyzed with Computational Fluid Dynamics (CFD) method. Outcome of the analysis is divided in two parts. First, different modes of sloshing depending on seismic excitation are identified. These modes are characterized by wave shapes, loads on structures and entrapped void. In the second part we capitalize on the framework of Integrated Deterministic-Probabilistic Safety Assessment (IDPSA) to quantify the risk. Specifically, statistical parameters pertaining to mechanical loads and void transport are quantified and combined with the deterministically obtained data about consequences.

Keywords: LFR, Sloshing, CFD, Reactivity Initiated Accident, IDPSA.

1. INTRODUCTION

European designs of Generation IV lead-cooled fast reactor (LFR) comprise of pool-type configurations with liquid lead or lead-alloy coolants (e.g. ELECTRA, ELSY, ETDR, ELFR, and MYRRHA) [1]–[6]. Pool-type LFRs have numerous inherent advantages such as compact and simple design, good neutronic properties, and natural circulation of lead coolant. However, high coolant density, low compressibility and presence of free surface raise safety concerns related to seismicity. More specifically, dynamic motion of free surface in a tank (also undergoing motion), referred to as *sloshing*, is of interest. The effect of sloshing on the primary system structures and reactor performance during a seismic event needs to be considered in the design and safety analysis phase. These issues are even more pronounced in the light of the Fukushima accident.

In this work, sloshing analysis is performed on the European Lead-cooled System (ELSY) design – a conceptual pool-type LFR with thermal power of 1500 MW (see Figure 1). Given the geometry of the tank containing the fluid, the *regime of sloshing* is determined by seismic excitation parameters. It is known that partially filled tanks, that ELSY primary system essentially is, are prone to violent sloshing, especially under near-resonance excitations.

Nowadays, seismic isolation is used to protect civil building, bridges, viaducts and even blocks of resident buildings. Implementation of a seismic isolation system is a promising solution to mitigate the adverse effects an earthquake may have on a nuclear reactor [7]. Seismic isolators are commonly used to reduce the displacements and forces in horizontal directions only. Isolation system adds damping to the structure and shifts the frequencies in the response spectra towards lower values (closer to natural frequencies of sloshing) [8]–[11] (see Figure 2). The regime of sloshing, then, naturally depends on the particular isolation system implemented.

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Figure 1: ELSY reactor configuration.

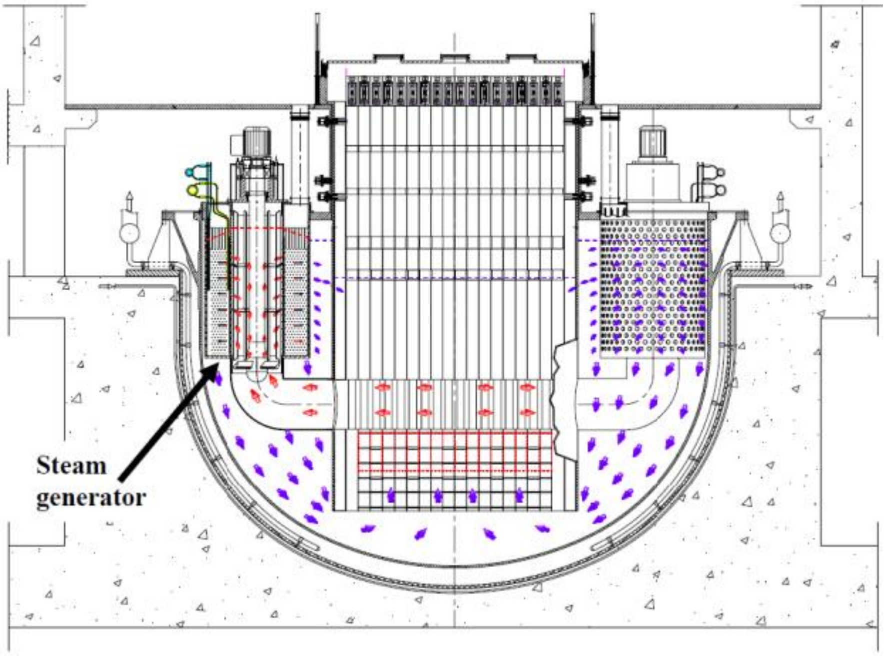
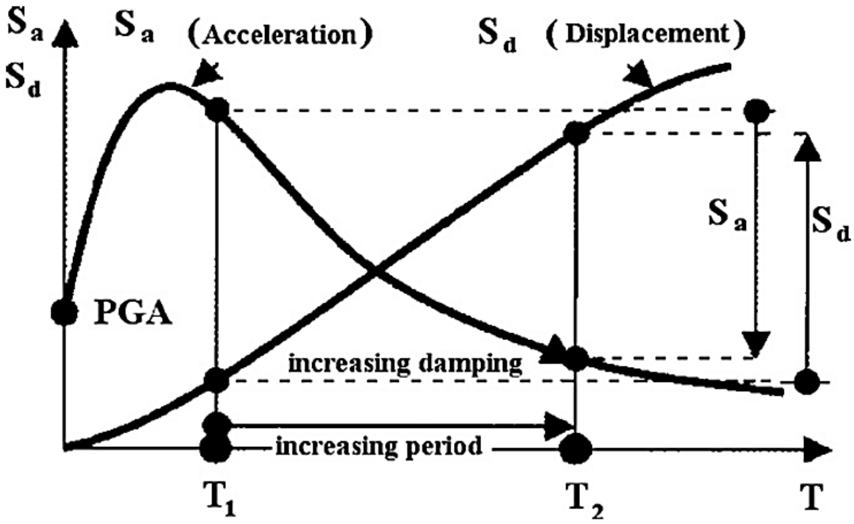


Figure 2: Effect of isolation system [8]**.**



Depending on the type of regime, consequences can be (i) dynamic loads that exceed the limits for structural integrity (fluid-structure interaction or FSI) and/or (ii) core damage due to reactivity initiated accident (RIA) or due to local deterioration of heat transfer (both induced by the void entrapped and transported to the core with primary coolant) [12]. RIA is a special issue in fast reactors where the spectral effect of coolant voiding is generally positive [13], [14]. This is because of reduced neutron moderation and capture leading to more and higher energy neutrons in the system. The effect is especially significant in the core region, where neutron leakage has small effect. Local heat transfer deterioration in the core can result in dry-out of a fuel rod.

2. METHODOLOGY

In this work the phenomena relevant to LFR coolant sloshing is studied using Computational Fluid Dynamics (CFD). A Probabilistic Safety Assessment (PSA) methodology has been applied in the quantification of risk related to sloshing [15].

2.1. Geometrical Model

As present work is an exploratory study to map the sloshing regimes in the seismic excitation space, two-dimensional (2D) geometry is regarded suitable. The computational domain represents a 2D rectangular slice between the inner circular vessel and outer vessel in ELSY downcomer. Vertically, the domain includes the whole gas space and to a certain depth, the lead coolant. See Figure 3and Figure 4 for illustration. The domain is 3.2 m wide and 2.6 m high (Figure 5).

Figure 3: Region of interest encompassing the free surface in ELSY downcomer.

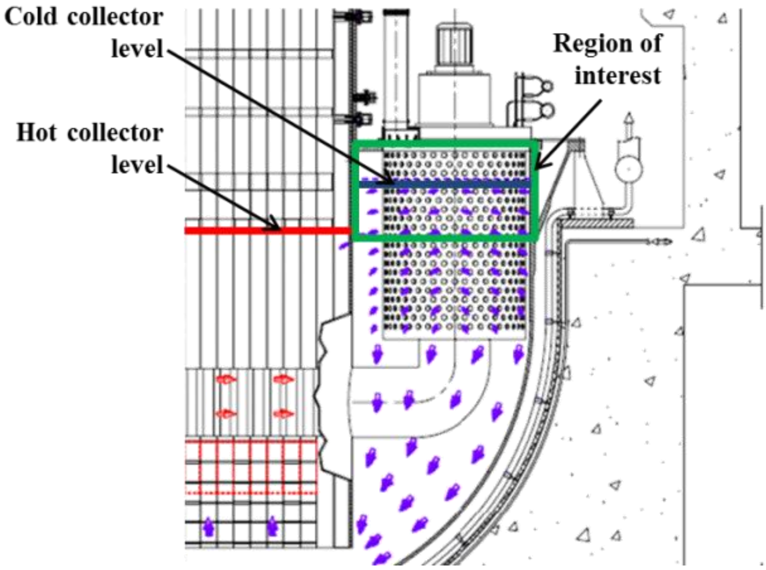


Figure 4: Region of interest between steam generators from the top.

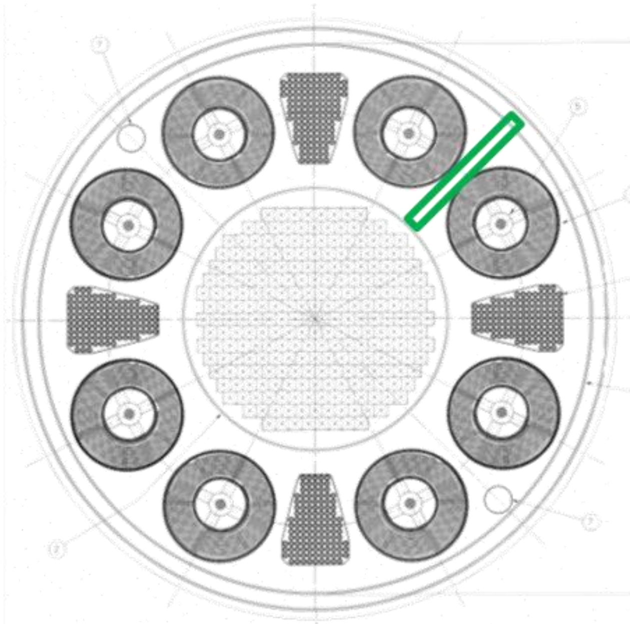
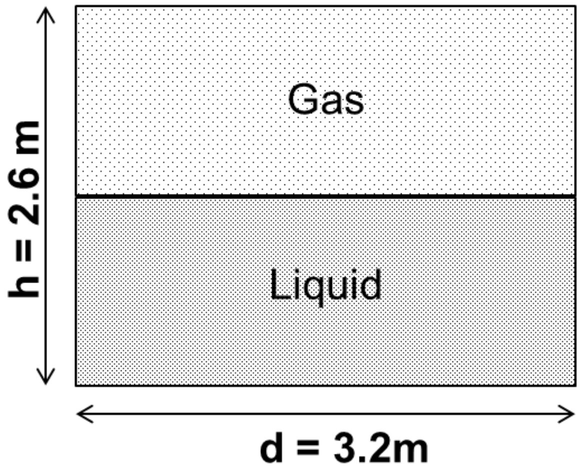


Figure 5: 2D geometry with characteristic dimensions.



2.2. Numerical Model

Commercial CFD software ANSYS FLUENT 14.5 was used for the simulations. Two-dimensional U-RANS with realizable k-ε turbulence model was chosen as the model for analysis. Lead coolant is modelled as incompressible liquid and argon as compressible gas. Material properties for liquid lead at 400°C are defined according to [16]. Argon properties are taken from the FLUENT built-in material database. Volume of Fluid method with surface tension modeling was used for tracking the interface between phases. Tank walls are assumed to be rigid.

Seismic excitation of the system was modelled by a source term in the momentum equation described by a sinusoidal function (see Eq. (1)):

$$A(t) = S_a \sin(\omega t) \tag{1}$$

where $S_a[m/s^2]$ is the amplitude of seismic acceleration function and $\omega = 2\pi f \ [rad/s\,]$ is the angular frequency.

Adaptive time-stepping was used in time-dependent cases to ensure the Courant number less than 0.5. As initial conditions, velocity of both phases is zero everywhere and the domain is vertically divided into two parts – lower half for liquid and upper half for gas.

2.3. Mesh Sensitivity Study

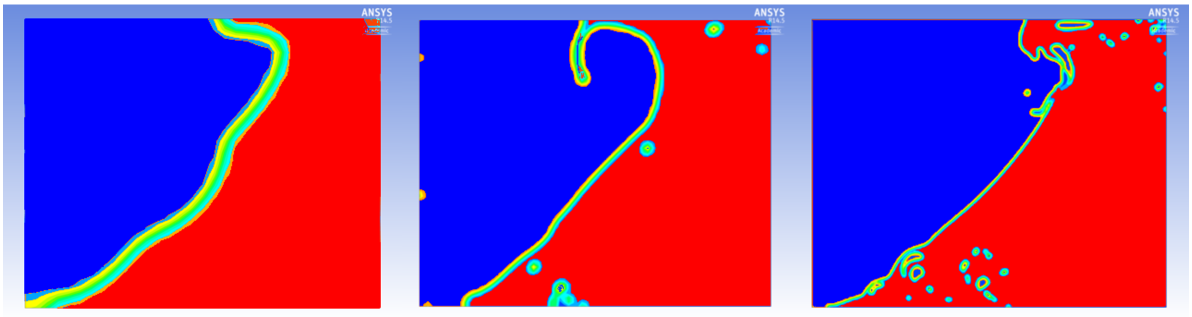
In order to analyze the influence of the mesh resolution on the results, a sensitivity study was carried out. Test case is a sudden activation of x-momentum source with magnitude equal to gravity. Solution showing the free surface at an angle of 45° also verifies that the problem setup via User Defined Functions (UDFs) is done correctly. Three different resolution quadrilateral meshes were tested (see Table 1).

Table 1: Characteristics of the mesh sensitivity study.

Cell size	Mesh resolution	Simulation time (10 s)	Average time step
10 cm	32x26	1 h 13 min	10 ms
4 cm	80x65	3 h 18 min	3.4 ms
2 cm	160x130	10 h 30 min	1.5 ms

Figure 6 illustrates the degree of detail in the flow structures resolved with three selected meshes. For the sloshing analysis in this paper mesh with the cell size of 4 cm (80x65 elements) was finally chosen based on two aspects: (i) significantly shorter calculation time, and (ii) sufficient qualitative resolution of large scale wave behavior.

Figure 6: Resolution of flow structures on different meshes.



2.4. Seismic Boundary Conditions

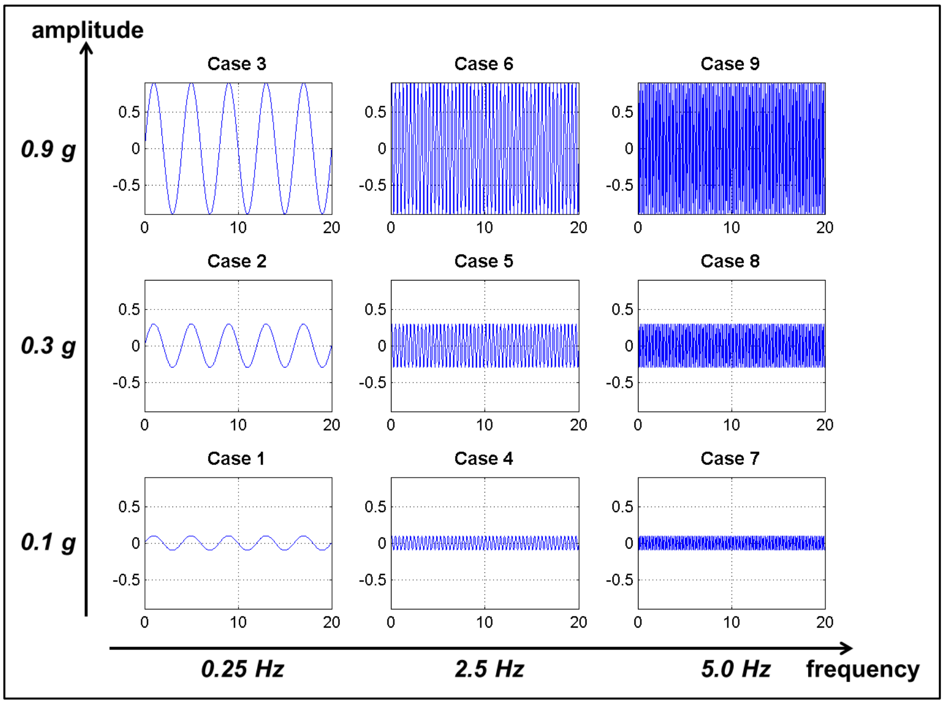
Ranges of seismic excitation parameters considered here are selected to cover reactor specific conditions. It was shown in the ELSY project that the 1st fundamental frequency in the seismic response spectra at the reactor level is shifted from 2.78 Hz to 0.58 Hz due to implementation of seismic isolation system [10]. Fundamental frequencies of the synthetic floor response spectra for twelve different isolator/soil/seismicity level combinations, obtained in the SILER project, are in the range of 0.25-4.5 Hz [17]. Regarding accelerations, application of isolation system with 7% damping reduce the maxima from 1.3 g (non-isolated building) to 0.09 g-0.25 g depending on the isolator used [10]. Limits proposed in [17] for the peak spectral acceleration (at any point in the isolated structure), are shown in Table 2.

Table 2: Design limits.

Seismicity Level	Displacement	Peak Spectral Acceleration
Operating Basis Earthquake (OBE)	7 cm	Horizontal – 0.2 g, Vertical – 0.45 g
Design Basis Earthquake (DBE)	22 cm	Horizontal – 0.6 g, Vertical – 1.4 g
Beyond Design Basis Earthquake (BDBE)	70 cm	Horizontal – 1.2 g, Vertical – 4.2 g

Considering the information above a simulation matrix is defined in Figure 7. Note that 0.9 g instead of BDBE acceleration limit of 1.2 g is used as a maximum acceleration in this analysis.

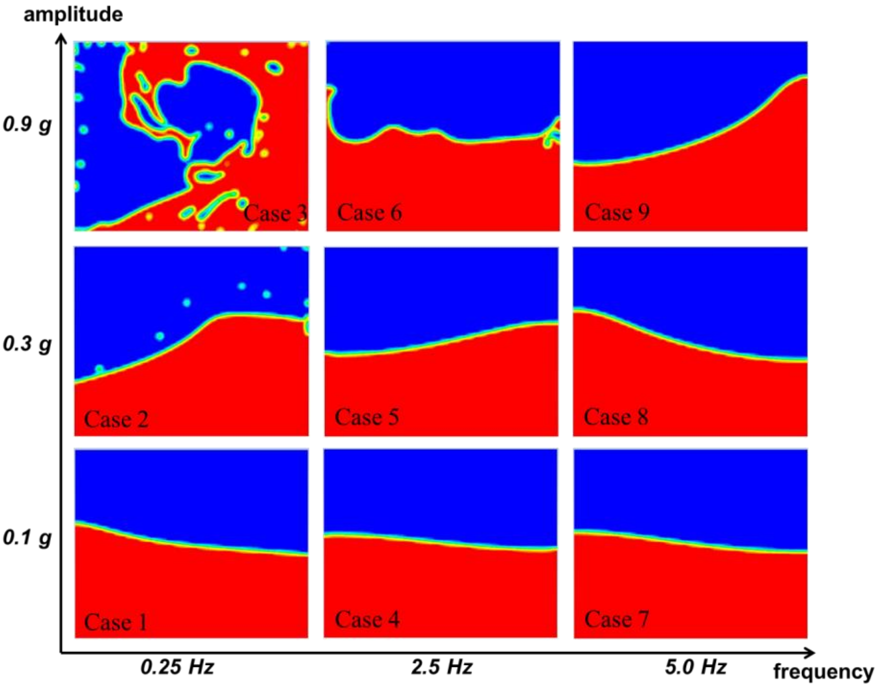
Figure 7: Excitation spectra used in the analysis.



3. RESULTS

Transient time for all cases was 20 s. Figure 8 represents a map with characteristic flow structures for every simulated case. It is clear that the conditions leading to violent sloshing are located in the upper left part of the map, the region with small frequencies and high amplitudes. Apart from this particularly active sloshing region there is no significant development of breaking waves expected.

Figure 8: Map of the characteristic flow structure.



Highest forces on the walls occur during cases with high amplitude seismic oscillations (see Cases 3, 6 and 9 indicated with diamond symbols in Figure 9, Figure 10 and Figure 11). Maximum pressures exceed 1 MPa with a maximum of 2.3 MPa at the left wall in Case 3.

Figure 9: Maximum pressure at the left wall.

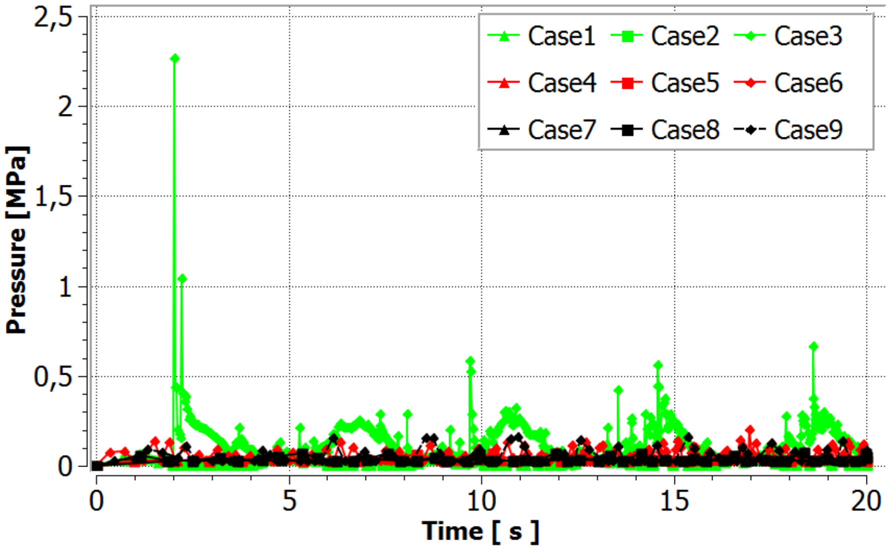


Figure 10: Maximum pressure at the right wall.

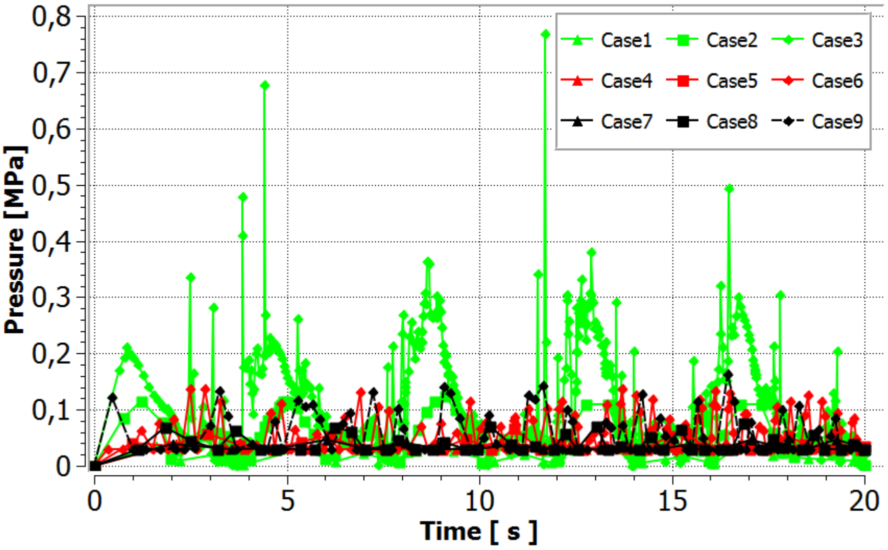
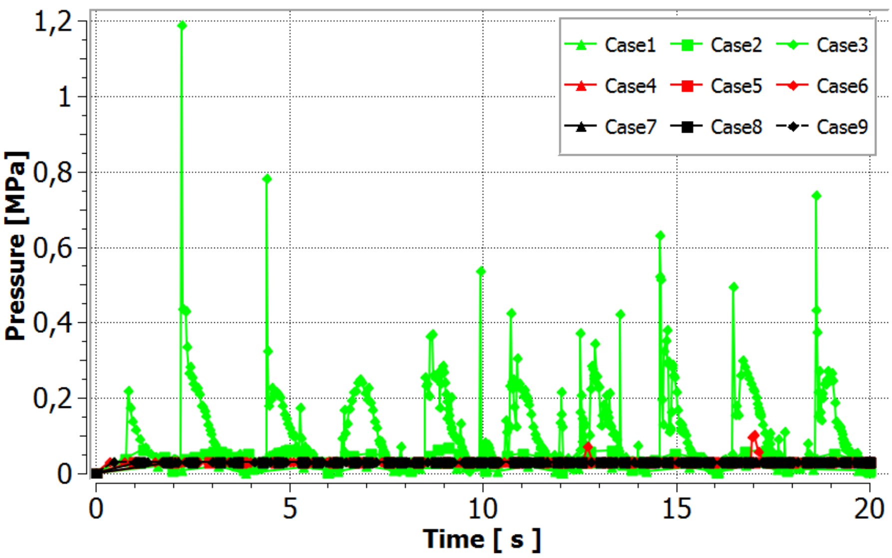


Figure 11: Maximum pressure at the top wall.



Velocities higher than 100 m/s are observed in the gas phase region where small lead droplets are falling down due to combination of gravity and seismic momentum (Figure 12).

Wave height monitor shows about 18-19 peaks even at high frequency excitations (see Figure 13) implying that the natural frequency of the wave of is about 0.5 Hz. This is in a good agreement with natural frequency of 0.46 Hz obtained analytically for sloshing in a rigid tank with the dimensions used in this work [18].

More simulations were performed in order to further investigate the active sloshing area of the map. With information from every new simulation next case was selected. Simulation of Case 10 – Case 14 provide more resolution in the region close to natural frequency of the system.

Finally, Figure 14 summarizes all simulated 2D sloshing cases. Lines in the figure indicate the boundaries between active and non-active sloshing. An interpolated surface of peak pressures as a function of seismic excitation parameters shown in Figure 15 is in accordance with the sloshing regime map representation.

Figure 12: Maximum velocities in the whole domain.

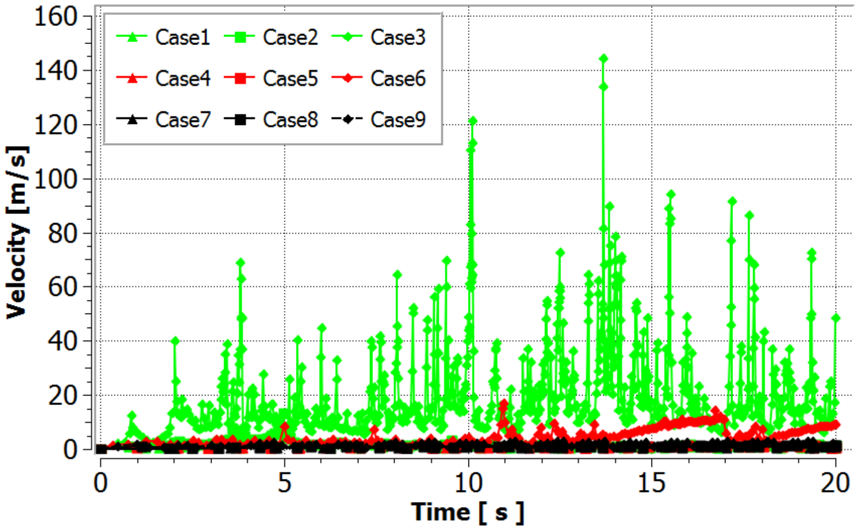


Figure 13: Maximum height of the liquid phase.

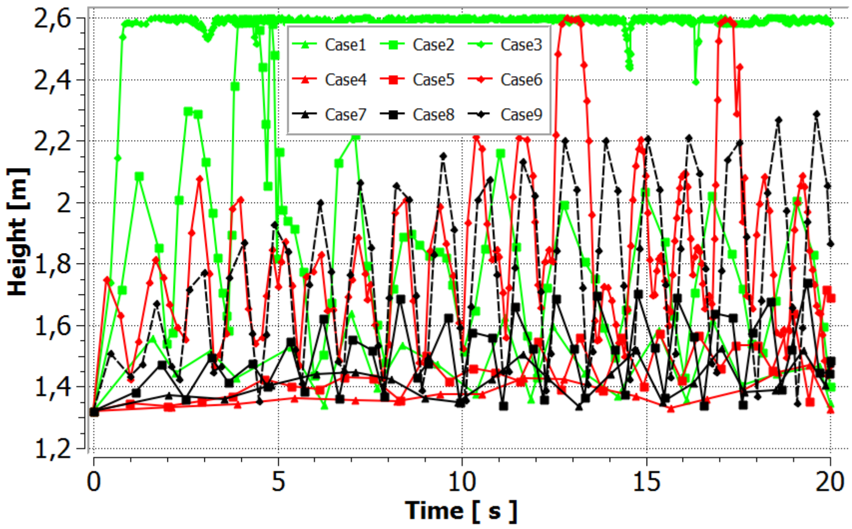


Figure 14: Revised sloshing map.

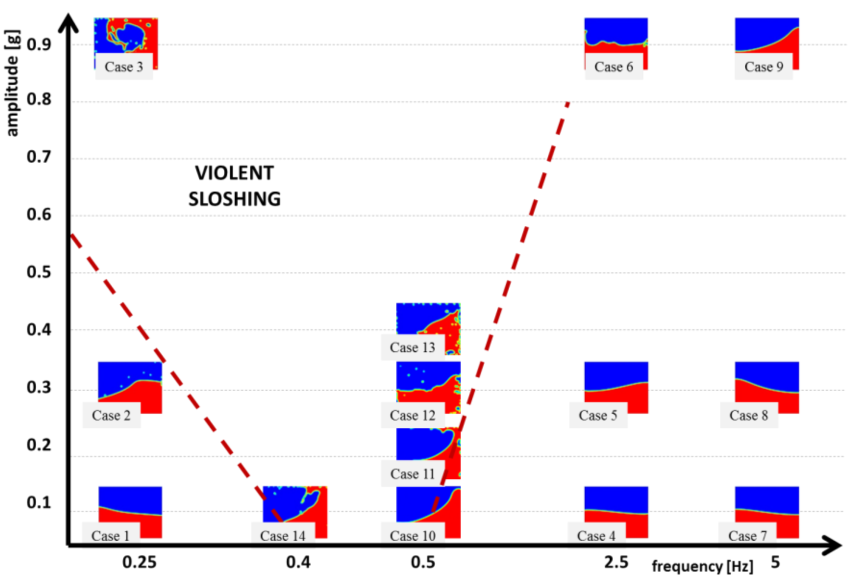
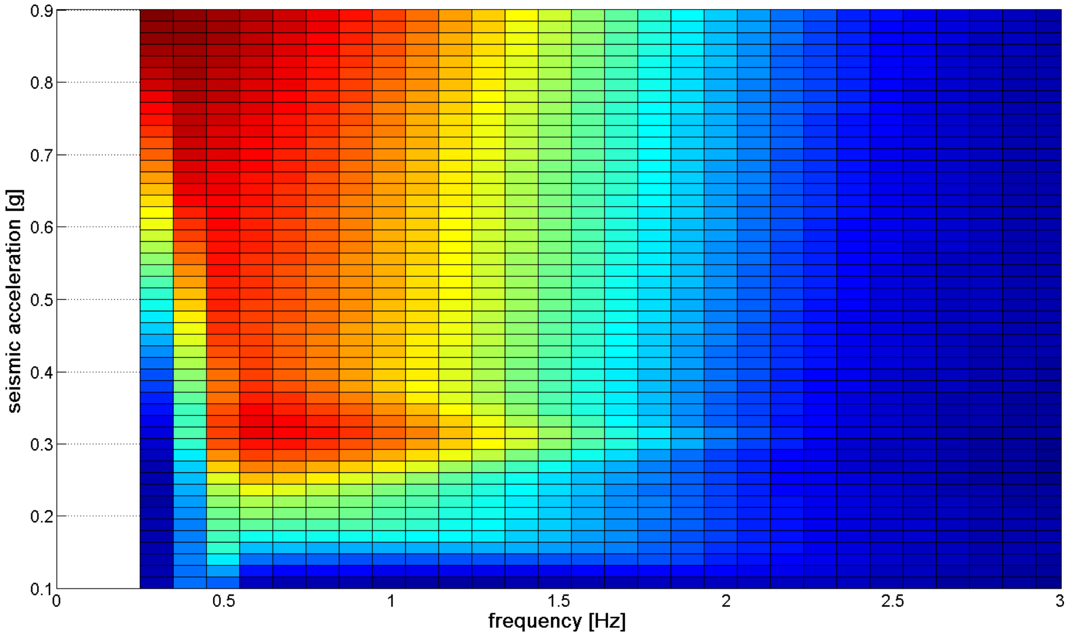


Figure 15: Interpolated surface of peak pressures during sloshing simulation as a function of seismic excitation.



4. DISCUSSION

An exploratory study of sloshing phenomena in the pool of a lead cooled fast reactor is carried out. The results of 2D CFD analysis suggest that near-natural frequency and high amplitude excitation leads to strongest sloshing with highest waves, velocities, and pressure peaks at the walls. It was shown that excitations with frequency of 0.4-0.5 Hz lead to sloshing already at relatively low (0.1 g) acceleration amplitudes.

Predicted pressure peaks around 1 MPa at the top wall suggest that coolant sloshing phenomena should be addressed in the design phase of an LFR as a possible source of risk.

Entrapment of gas bubbles due to splashing needs further investigation. Even though it seems that the length of the free surface domain in ELSY is not sufficient for development of large breaking waves, splashing can still lead to entrapment of void in the coolant.

5. OUTLOOK

Analysis of sloshing with real seismic excitation time-histories (or oscillating waves with multiple harmonics) as boundary conditions must be considered. Moreover, a three-dimensional analysis is required to improve the understanding of multi-dimensionality effects on the sloshing phenomena.

Acknowledgements

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References

[1] "A Technology Roadmap for Generation IV Nuclear Energy Systems," Dec. 2002.

[2] D. Mattioli and F. Roelofs, "Roadmap for LFR Development," Bologna, 2013.

[3] J. Wallenius, E. Suvdantsetseg, and A. Fokau, "ELECTRA: European Lead-Cooled Training Reactor," *Nucl. Technol.*, vol. 177, pp. 303–313, 2012.

[4] A. Alemberti, J. Carlsson, E. Malambu, A. Orden, L. Cinotti, D. Struwe, P. Agostini, and S. Monti, “ELSY — European LFR Activities,” *J. Nucl. Sci. Technol.*, vol. 48, no. 4, pp. 479–482, 2011.

[5] A. Alemberti, J. Carlsson, E. Malambu, A. Orden, D. Struwe, P. Agostini, and S. Monti, “European lead fast reactor—ELSY,” *Nucl. Eng. Des.*, vol. 241, no. 9, pp. 3470–3480, Sep. 2011.

[6] H. Aït Abderrahim, P. Baeten, D. De Bruyn, and R. Fernandez, “MYRRHA - A multi-purpose fast spectrum research reactor,” in *Energy Conversion and Management*, 2012, vol. 63, pp. 4–10.

[7] M. Forni, “Seismic isolation of nucler power plants,” pp. 1–8, 2011.

[8] A. W. Taylor and T. Igusa, Eds., *Primer On Seismic Isolation*. American Society of Civil Engineers, 2004.

[9] O. R. Jaiswal, S. Kulkarni, and P. Pathak, “A Study On Sloshing Frequencies Of Fluid-Tank System,” in *The 14th World Conference on Earthquake Engineering*, 2008, no. 1963.

[10] J. Nezo and A. Carrasco, “Seismic Response Spectra of the Reactor Building,” Madrid, 2007.

[11] R. Lo Frano and G. Forasassi, “Isolation systems influence in the seismic loading propagation analysis applied to an innovative near term reactor,” *Nucl. Eng. Des.*, vol. 240, no. 10, pp. 3539–3549, Oct. 2010.

[12] P. Kudinov and T. Dinh, “Evaluation approach and case set-up for simulation of consequences of the SGTR event,” 2010.

[13] C. Döderlein, K. Tucek, J. Cetnar, P. Stanisz, G. Grasso, and A. Travleev, “Definition of the ELFR Core and Neutronic Characterization,” 2013.

[14] C. Petrovich, G. Grasso, P. Sciora, C. Artioli, and F. Rocchi, “Definition of the ETDR Core and Neutronic Characetization,” 2013.

[15] IAEA, “Probabilistic Safety Assessment for Seismic Events,” Vienna, 1993.

[16] V. Sobolev, “Database of thermophysical properties of liquid metal coolants for GEN-IV Database of thermophysical properties of liquid metal coolants for GEN-IV,” Mol, 2011.

[17] J. Gallego, “Description of Systems , LFR,” Madrid, 2012.

[18] G. W. Housner, “The Dynamic Behavior of Water Tanks,” *Bull. Seismol. Soc. Am.*, vol. 53, no. 2, pp. 381–387, 1963.