SEISMIC ANALYSIS OF REACTOR ASSEMBLY FOR PROTOTYPE FAST BREEDER REACTOR

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ABSTRACT

Seismic analysis of reactor assembly of 500 MWe pool type fast breeder is carried out to ensure that certain functional limits and RCC-MR design criteria are respected. The important functional requirements that are addressed in this paper are: (i) it should be possible to shutdown the reactor in case of demand for SCRAM from the plant protection system during a seismic event, (ii) the reactivity insertion because of possible compaction during dynamic displacements of core under seismic event and relative vertical displacements between absorber rods and fuel sub-assembly, should not result in super prompt criticality, (iii) there should not be any sodium slug impact on the top shield due to sloshing and (iv) there should not be any mechanical interaction between the adjacent shells. The primary stress limits specified in RCC-MR code are also respected.

Seismic analysis is carried out on the reactor assembly components using CAST3M considering the fluid-structure interaction effects. The seismic excitations at the reactor assembly support location at the reactor vault, derived from results of seismic analysis of entire nuclear island completed in the first phase, are employed for the analysis. An axisymmetric finite element analysis is performed with Fourier option to account for the circumferential load variations, taking in to account fluid structure interaction effects. Based on the analysis, it is demonstrated that the reactor assembly components meet both functional and structural integrity requirements.

INTRODUCTION

A 500 MWe Prototype Fast Breeder Reactor (PFBR) is under construction at Kalpakkam. PFBR is a sodium cooled pool type reactor where the entire radioactive primary sodium circuit components including the core are housed within a single vessel called main vessel. Fig.1 shows the schematic of reactor assembly (RA). The main vessel (MV) is a large thin walled shell of 12.9 m diameter with 25 mm thickness in its cylindrical portion. The main vessel contains about 1150 t of radioactive liquid sodium and supports the core and internals such as core support structure, grid plate, thermal baffles and inner vessel. The weight of main vessel along with two thermal baffles attached with it is about 200 t. The total weight of core and internals is about 750 t, which is transmitted to the triple point on the main vessel dished end at the bottom in the form of ring load. The top shield serves as the cover for main vessel and is basically box type structure filled with concrete. It supports primary sodium pumps, intermediate heat exchangers (IHX), control plug (CP) and in-vessel core subassembly handling systems. The weight of top shield along with its components is about 1200 t. With all the components and sodium, the reactor assembly weighs about 3700 t. The reactor assembly is supported at the top of reactor vault, which is an annular reinforced concrete structure resting on the base raft.

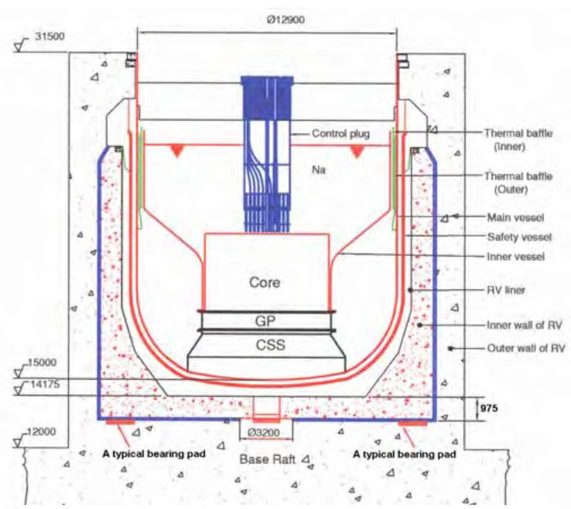


Fig.1 Schematic of FBR reactor assembly

In this paper, structural characteristic of FBR components w.r.t seismic loadings, seismic design criteria, finite element discretisation of structures, modal analysis for determining natural frequencies and associated mode shapes, seismic response analysis to determine peak displacements and stresses in the critical locations and design check for the functional and stress limits are covered.

STRUCTURAL CHARACTERISTICS OF FBR COMPONENTS

With the use of sodium coolant which remains in liquid state up to about 950^{o}C, there is no need of pressurising the sodium for the normal operating temperature of 550^{o}C and hence the design pressure is low for the reactor assembly shell structures. However, due to a large temperature difference (150^{o}C) between hot and cold sodium pools co-existing within the main vessel, the thermal stresses developed in the shells during steady state and transient conditions are generally higher. In view of low design pressure, high thermal stress and economic considerations, thin walled shell structures are chosen. PFBR being pool type, the main vessel needs to be a large size shell. The diameter to thickness ratio for the cylindrical portion of the main vessel is 516 (12900 /25) and hence it becomes very slender. The large sodium mass (1150 t) which is contained in the vessel, adds high mass inertia. Since the reactor assembly is supported at the top, the main vessel is an over-hung structure. Because of these features, the predominant natural frequencies lie in the range 5-20 Hz, where the dynamic response amplifications are higher since the earthquake has high energy content in this range of frequencies. Hence, the seismic event imposes relatively high mechanical loadings, which decide the minimum wall thickness for the vessels.

SEISMIC DESIGN CRITERIA FOR THE REACTOR ASSEMBLY COMPONENTS

PFBR is designed for two levels of earthquake, called operating basis earthquake (OBE) and safe shutdown earthquake (SSE). The recommended peak ground acceleration (PGA) values are 0.078 g and 0.156 g for OBE and SSE respectively in the horizontal direction and 0.052 g and 0.104 g in the vertical directions [1]. Among many requirements specified for the seismic design, the following design criteria are relevant to the present scope:

a) The peak of the reactivity oscillation during earthquake should be < 0.5 $. In order to ensure this, the maximum relative vertical displacement between the absorber rod and fuel sub-assemblies should be less than 11 mm.
b) Sodium ejection to the reactor containment building through the top shield penetrations in case of sodium impact due to sloshing, should be prevented. For this, the maximum sloshing height should be less than the cover gas height (0.8 m).
c) There should not be any mechanical interaction between the adjacent shells. To ensure this, the maximum relative radial displacement between the shells should be less than the respective minimum available gaps.
d) The stresses generated in the components including those caused by self weight and static pressure, should be less than the appropriate primary stress limits specified by RCC-MR: edition 2002 [2]. The resulting stresses due to OBE combined with normal mechanical loadings should respect level A stress limits and the stresses due to SSE and normal mechanical loadings, should respect level D stress limits.

SEISMIC EXCITATIONS AT REACTOR ASSEMBLY SUPPORT

The basic seismic input data is site dependent design response spectrum (DRS) corresponding to 5% damping (target spectrum). Three uncorrelated synthetic time histories are generated compatible to the target spectrum, to apply 3 mutual perpendicular directions at the base of raft. Subsequently 3D seismic analysis of nuclear island including all the essential buildings and base raft is performed and the acceleration time histories in two horizontal and one vertical directions are extracted at reactor assembly support location. Fig.1 shows the finite element model of nuclear island connected building (NICB). From each of these acceleration time histories, respective floor response spectra (FRS) are derived as per the guidelines recommended in the ASME: Appendix-N [3]. The damping values of 2 % for OBE and 4 % for SSE are used, applicable for analysis of welded structures as per ASME:Appendix-N. Since analysis is axisymmetric, the conservative spectrum is chosen from the two spectra available for the horizontal direction. Fig.3 shows the FRS generated at the reactor assembly support location.

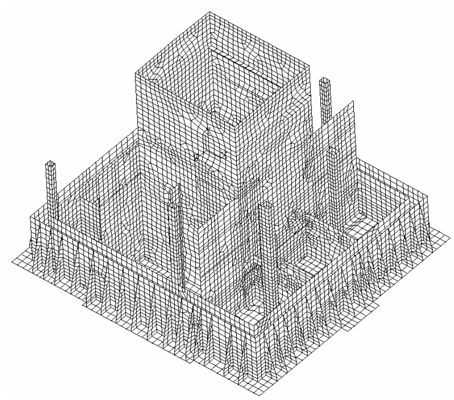


Fig.2 FEM model of NICB for seismic analysis

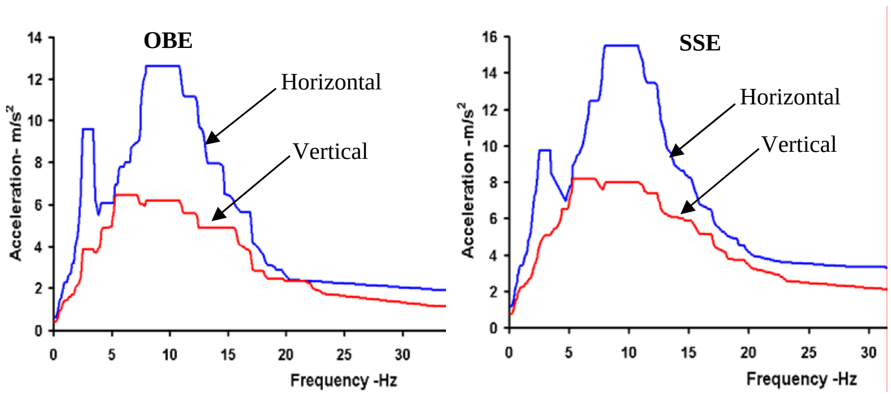


Fig.3 Floor response spectra at reactor assembly support

FINITE ELEMENT DISCRITISATION OF REACTOR ASSEMBLY

Computer code CAST3M developed by CEA-France is used for the analysis. The components which are essential to be included in the numerical simulation are main vessel, thermal baffles, inner vessel, core support structure (CSS), grid plate (GP), core, control plug, top shield and support shell. Except main vessel, two thermal baffles (weir shell and inner baffle) and inner vessel, other components are not symmetric shell structures and hence equivalent shell models are developed by conserving their total masses and simulating the static deflections under the gravitational forces. By this approach, the fundamental natural frequencies which are associated with the bending modes are simulated.

The shell structures are modeled with '2-noded thin shell element'. The sodium volume is modeled with '4-noded quadratic element'. This apart, interfaces of sodium and shells are modeled using 'fluid-structure interaction element'. There are five sodium free surfaces for (1) hot pool of sodium in the inner vessel, (2) hot pool confined by the control plug, (3) cold pool (plenum between inner vessel and inner baffle), (4) feeding collector (sodium plenum in the annular space between main vessel and weir shell), and (5) restitution collector (sodium plenum between inner baffle and weir shell). At these sodium free surfaces, appropriate boundary conditions, which relate gravitational forces and pressure gradients are imposed in the form of special line elements. Fourier decomposition option is chosen to include the circumferential variation of loadings.

Other internals such as primary sodium pumps, intermediate heat exchangers and fuel handling components do not affect the results and hence, not included in the simulation. However, their masses are lumped on the top shield to simulate the natural frequency of top shield accurately. It is worth mentioning that the surface of the equivalent shell employed to replace core is also considered as one of the fluid shell interfaces to consider the effects of fluid structure interaction. The perforated shell of the control plug has been modelled as equivalent solid shell. Therefore the fluid communication between the hot pool sodium within and outside of the control plug is not modelled. Also the fluid communication between the feeding collector and the cold pool through the 24 cooling tubes has not been modelled.

Optimum mesh size is used to get converged results. In order to determine the dynamic pressures on the fluid-shell interfaces accurately, very fine fluid mesh is adopted along the shell surfaces. The finite element model thus developed for the entire computational domains are shown in Fig.4.

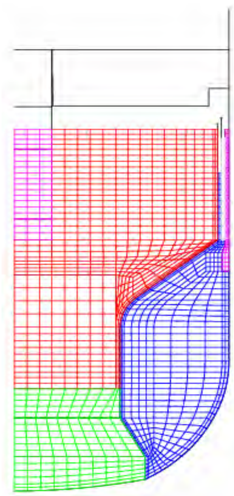
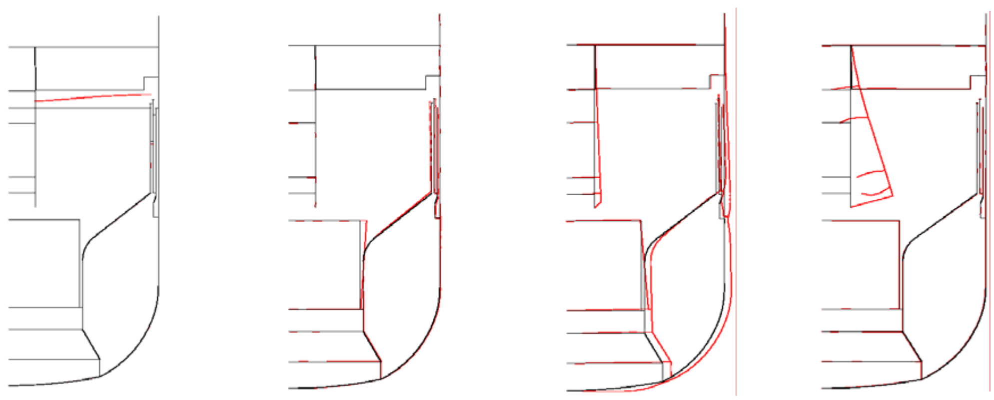


Fig.4 FE mesh of RA

The total mass accounted in the finite element simulation including sodium is about 3700 t. The top of the support shell is fixed at which support excitations are applied. The material is austenitic stainless steel type 316 LN for the components incorporated in the model except for the top shield, the material of which is A48-P2 carbon steel. The required material properties at appropriate temperatures are taken from RCC-MR: Appendix-A3 [4].

NATURAL VIBRATION ANALYSIS

Natural vibration analysis is carried out to determine the natural frequencies up to 50 Hz with the associated mode shapes and modal mass participations which are essential for the subsequent seismic analysis by modal superposition method. A few important mode shapes that are depicted in Fig.5 indicating the respective natural frequencies are: sloshing of hot pool (0.25 Hz), vibration mode of core subassemblies (3 Hz), bending mode of main vessel (7.7 Hz) and bending mode of control plug (8.9 Hz).



Hot pool Sloshing: 0.25 Hz Bending of core: 3 Hz Bending of MV: 7.7 Hz Bending of CP: 8.9 Hz

Fig.5 Important vibration mode shapes

SEISMIC RESPONSE ANALYSIS

Time history analysis is carried out on the axisymmetric model with Fourier option. In the Fourier option, dynamic responses for the horizontal and vertical seismic excitations are determined separately by choosing harmonic wave number (n) equal to '0' for vertical excitation and '1' for horizontal excitations. The time step chosen is 0.001 s. Analysis is carried out up to 20 s. Damping values used are 2 % for OBE and 4 % for SSE. The important results are given below:

Sloshing Heights

Table-1 shows the peak sloshing heights of various sodium free levels under SSE. Fig.6 shows the time variation of hot pool free level. which indicates the maximum sloshing height of `642 mm.

Table-1: Sloshing heights - mm

Sodium pool	X		Y	
	OBE	SSE	OBE	SSE
Feeding collector	151	239	194	267
Restitution collector	110	166	154	202
Cold pool	488	635	436	594
Hot pool in inner vessel	463	591	393	642
Hot pool in control plug	7.0	5.4	7.4	4.7

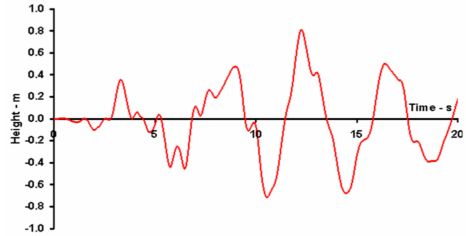
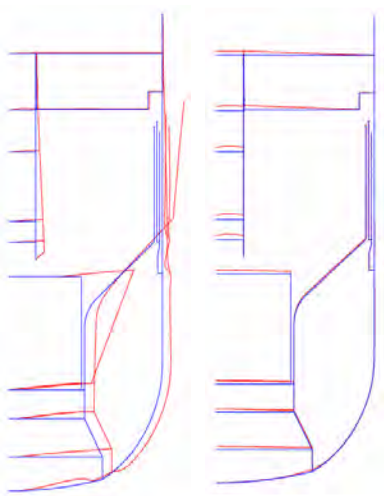


Fig.6 Sloshing of hot pool in inner vessel

Displacements

The SSE yields higher displacements compared to OBE. The important displacements are extracted from the analysis. Fig.7 shows the deformations of various shells in the reactor assembly both in horizontal and vertical directions. The maximum relative horizontal displacements between vessels are extracted and presented in table-2. The main vessel bottom moves about 9 mm in the horizontal direction and 7.4 mm in vertical direction. The gap between inner vessel and thermal baffle is reduced by 46 mm. The time variation of relative vertical displacements of absorber rods (AR) with reference to the core is shown .in Fig.8. The maximum relative vertical displacement between control subassemblies and absorber rods (AR) is 5.2 mm which is important for the investigation of reactivity oscillations during SSE.



Horizontal Vertical

Fig.7 Peak displacements (SSE)

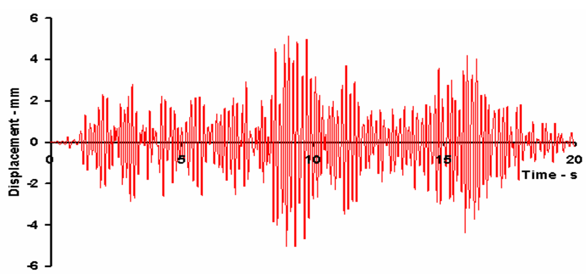


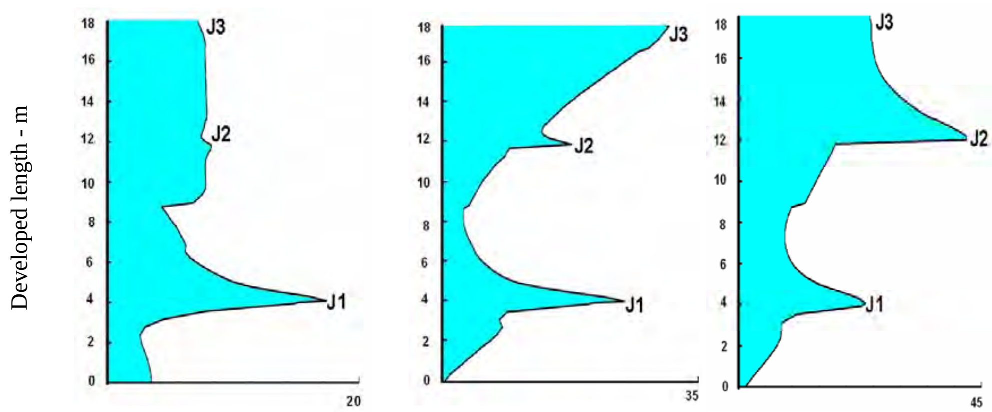
Fig.8 Relative displacement between core and AR

Table-2: Important displacements (SSE) - mm

Components	X	Y
Main vessel bottom	8.8	7.4
Inner vessel – Inner baffle	46	44
Inner baffle – Outer baffle	0.3	0.4
Outer baffle – main vessel	1.5	1.3

Stress Distributions

The distributions of maximum longitudinal and shear membrane stresses are depicted in Fig.9. The peak stresses at critical locations, viz. triple point and top shield junction, are given in table-3.



a. σ_{lm} - vertical seismic   b. σ_{lm} - horizontal seismic   c. τ_m - horizontal seismic

Fig.9 Stress distribution in main vessel under SSE

(J_1 – triple point, J_2 – weir shell junction; J_3 – top shield junction)

Table-3: Stresses at two critical locations – MPa

Location	Normal + OBE						Normal + SSE					
	σ_{lm}	σ_{hm}	τ_m	σ_{lb}	σ_{hb}	τ_b	σ_{lm}	σ_{hm}	τ_m	σ_{lb}	σ_{hb}	τ_b
Triple point	26	64	16	99	40	2	32	88	23	131	51	3
Top shield junction	60	05	23	07	03	0	64	05	26	8	03	0

DESIGN CHECK

Critical Displacements

The maximum sloshing height is 642 mm (Fig.6), which is lower than 0.8 m, the cover gas height. Under OBE, the maximum height is 463 mm which does not cause any impact either on the top shield or thermal shield hanging from top shield. The maximum relative vertical displacement between control subassemblies and absorber rods is 5.2 mm. which can cause a peak reactivity insertion of 0.25 $ under SSE. Since it is less than 0.5 $, there is no risk of super prompt criticality. It is also seen from table.2 that the maximum relative radial displacement is 48 mm between inner vessel and inner baffle which is less than the minimum gap between the shells, i.e. 90 mm. Hence, there is no risk of mechanical interactions.

Primary Stress Limit as per RCC-MR

As per RCC-MR [2], primary stress intensities under normal plus OBE and normal plus SSE should respect the following criteria:

$P_m \leq S_m$ and $P_m + P_b \leq 1.5xS_m$ for normal + OBE (level A loading)

$P_m \leq 2.4xS_m$ and $P_m + P_b \leq 3.6xS_m$ for normal + SSE (level D loading)

where S_m is the basic allowable stress intensity values given in RCC-Appendix A3 [4]. The individual stress components resulting from horizontal and vertical excitations are combined by ‘square root of sums of squares (SRSS)’ method. For e.g. $\sigma_{1\text{-srss}} = \sqrt{(\sigma_{1m-\text{horizontal}}{}^2 + \sigma_{1m-\text{vertical}}{}^2)}$.

For computing the net primary stress intensities, the stresses developed due to horizontal excitations (maximum values between X & Y excitations), dead load and hydrostatic pressure of sodium head are added. Among various load cases analysed, the maximum values of stress intensities thus computed are extracted and presented in table-4 for the design check for main vessel, inner vessel, control plug and thermal baffles. Fig.10 shows the distribution of stress intensities for main vessel and safety vessel.

Table-4 Primary stress intensities

Component	OBE		SSE	
	P_m	P_m+P_b	P_m	P_m+P_b
Main vessel	94	144	160	256
Inner vessel	127	135	155	164
Inner thermal baffle	28	43	30	49
Outer thermal baffle	30	46	33	52
Control plug	37	39	47	50

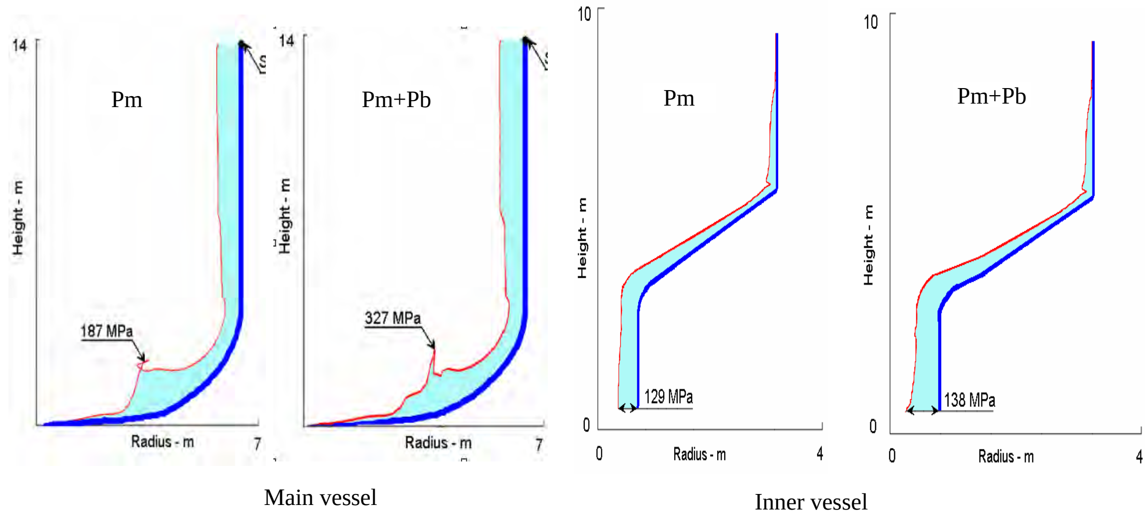


Fig.10 Primary stress intensity for main vessel and inner vessel

Table-4 shows that the inner vessel is the most critical component for load combinations under OBE. The primary stress limits for the inner vessel are not respected since the calculated primary membrane stress intensity (127 MPa) is exceeding the respective allowable value of 106 MPa at the averaged temperature of the inner vessel at the critical location. This can meet the limit provided the peak ground acceleration (PGA) value is limited to 0.062 g. However, if the OBE is treated as as level C loadings, it can respect the level C stress limits. For other components, the stress limits are met with good margins. From the table-4, it is also clear that the OBE controls the design rather than SSE as far as stress limits are concerned.

CONCLUSION

The displacements developed under SSE and stresses developed under OBE are the critical parameters that have been checked for meeting both functional and stress limits. The amplitude of reactivity oscillation due to the vertical displacements of the absorber rods w.r.t core is 0.25 $ which is less than 0.5 $. The maximum sloshing height under SSE is 810 mm marginally exceeding the cover gas height (800 mm), which is, however, not of concern from point of view of sodium impact. Further, there is of no concern of damage to thermal shield hanging below top shield under OBE (maximum sloshing height is 528 mm against available gap of 700 mm). The dynamic displacements of shells (maximum value is 48 mm) are less than the available minimum gaps between the adjacent ones (minimum gap guaranteed is 90 mm). Hence there is no fear of mechanical interactions between the shells.The RCC-MR stress limits are met at all the critical locations with comfortable margins under SSE. Under OBE, the inner vessel becomes critical for which RCC-MR primary stress limits are respected for the level C loading. Level A stress limits are met for the peak ground acceleration not exceeding 0.062 g. Hence, the OBE is treated as level C loadings for PFBR with the provision to inspect the vessel after an OBE. With this, the inner vessel meets the design requirement for the peak ground acceleration of 0.078 g.

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