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SEISMIC SSI ANALYSIS OF A REACTOR BUILDING COUPLED MODEL AND SEISMIC EVALUATION OF SELECTED STRUCTURES, SYSTEMS AND COMPONENTS (SSCs)

Yigit Isbiliroglu[1], Olivier Nusbaumer[3], Piyush Mehta[2], Yogesh Rathod[2], Matthew Haapala[4], Sai Chowdeswara Rao Korlapati[2], Nish Vaidya[5], Holger Senechal[6], Davide Kurmann[7]

[1] Engineering Director, RIZZO International, Pittsburgh, PA, USA (yigit.isbiliroglu@rizzointl.com)
[2] Structural Engineer, RIZZO International, Pittsburgh, PA, USA
[3] Principal Engineer and Technical Expert SES, Kernkraftwerk Leibstadt AG, Switzerland
[4] Senior Engineer, RIZZO International, Pittsburgh, PA, USA
[5] Vice President/Fellow, RIZZO International, Pittsburgh, PA, USA
[6] Structural Mechanics & Managing Director, KAE GmbH, Hausen, Germany
[7] Leiter Engineering Bautechnik, AXPO, Zürich Area, Switzerland

ABSTRACT

This Paper presents the seismic verification of selected components of the reactor coolant system (RCS) of the largest Swiss Nuclear Power Plant (Leibstadt) based on the coupled model seismic soil-structure interaction (SSI) analysis of the reactor building (RB). The seismic verification accounts for the updated seismic hazard basis and the associated ground motion input.

The seismic verification of the components of the RCS is performed based on a comprehensive seismic analysis using an aggregate coupled model of the RB. The coupled model explicitly represents the reactor pressure vessel (RPV), the main RPV internals and the pressurized enclosure of the RCS into the model of the RB.

The technical approach represents the state-of-the-art seismic SSI analysis. It employs the domain reduction method (DRM), Bielak et al. (2003), time history analysis in the standard ANSYS 2020 R1 (2020) platform to perform the seismic SSI analysis of the RB. Using this coupled model, seismic stresses and displacements at critical locations are obtained as the average of the quantities resulting from the three (3) sets of time histories input, enveloped from the lower bound (LB), best estimate (BE) and upper bound (UB) soil cases.

The normal operating load stresses (NOL) in the governing failure modes are based on existing design basis stress reports. The seismic evaluation obtains 1) factors of safety defined as the ratios of the allowable stresses to the stresses due to load combination; and 2) the seismic margins defined as the margin relative to seismic demand to the net seismic capacity. The RPV internals, e.g., control rod drive housing (CRDH) and fuel channels are also evaluated for seismic deformations to assess the seismic functional performance.

The evaluation demonstrates the robust performance of the RPV and internals including fuel assembly integrity, control rod insertion and fuel element lift-off. The deterministic verification of the RPV and internal components, the primary cooling system pressure boundary piping and selected key equipment including the steel containment are also evaluated to demonstrate a robustness of design and a sufficient seismic margin over and above the referenced ground motion.

INTRODUCTION

Kernkraftwerk Leibstadt (KKL) is Switzerland's newest and largest NPP commissioned in 1984. In 2015, the Swiss regulatory body (ENSI) enacted the new earthquake hazard levels ("EGA ENSI-2015") to be considered for future seismic evaluations of KKL's structure, system, and components (SSCs). The scope of the seismic evaluations described in regulatory guidelines ENSI-AN-8567 (2014), particularly of the components of the RCS, is significantly more extensive than the previously requested Post-Fukushima seismic margin assessments. ENSI-AN-8567 (2014) guidelines require that the seismic verification of components in the pressure boundary of the RCS should be based on the seismic analysis of the coupled aggregate RB model. The coupled RB model combines the analytical representation of RB structure, the RPV and internals, and the piping and equipment of the pressurized enclosure of the RCS up to the second main steam isolation valve. As described in a companion paper (Rathod et al., 2022), this regulatory requirement is accomplished by performing the seismic SSI analysis using the DRM, Bielak et al. (2003), and the ANSYS APDL platform (ANSYS 2020 R1, 2020).

The full scope of the seismic verification of the RCS is accomplished in four (4) primary tasks as summarized in Figure 1 below. After briefly summarizing the development and analysis of the coupled model, this paper addresses Tasks 2 through 4. Tasks 2 through 4 are facilitated by calculation scripts which perform and document the verification analysis, and obtains deterministic seismic margins (SM):

$$SM = \frac{S - Dns}{Ds} \tag{1}$$

where, S = Capacity of component based on SIA and KTA 3211.2 (2012)
Dns = the non-seismic demand (due to normal operating loads, such as dead weight, normal operating pressure and mechanical loads)
Ds = the seismic demand for the review level earthquake (RLE)

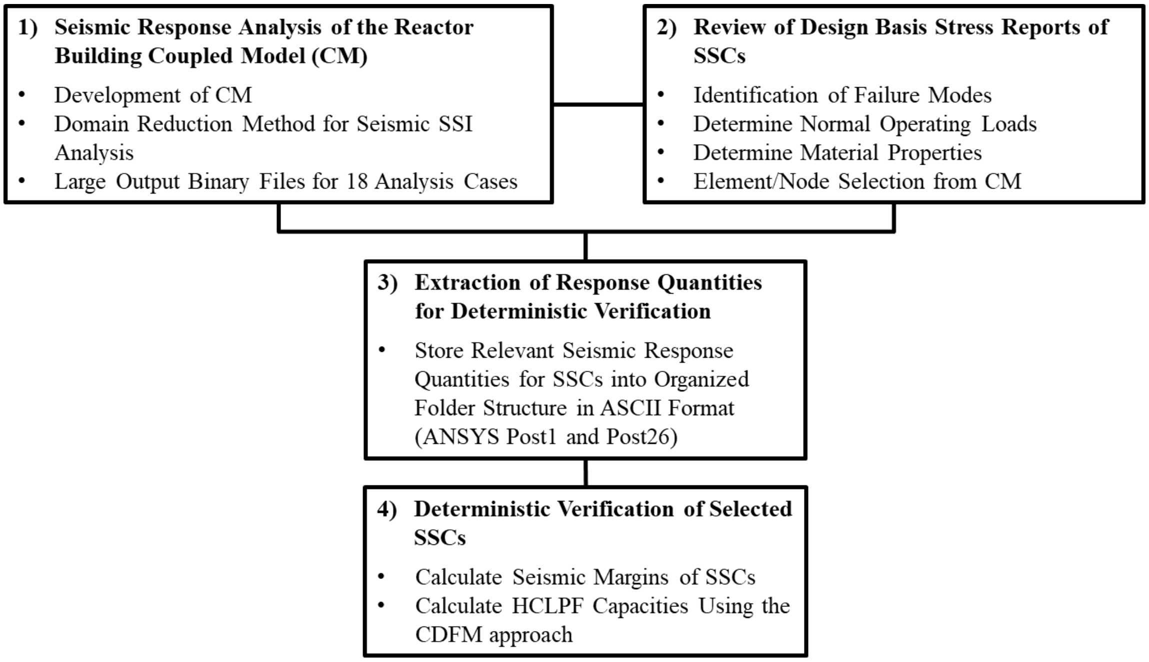

Figure 1. Technical approach flowchart

COUPLED MODEL SEISMIC SSI ANALYSIS OF THE REACTOR BUILDING

Figure 2 identifies the different parts of the coupled model as follows:

- A sufficiently refined RB structure model capable of accommodating the coupling points of steel structures serving as pipe supports;
- RPV model, including internals in sufficient detail to allow extraction of seismic forces, moments and stresses;
- Piping models including the recirculation loops of the RCS, the feed water and the main steam lines up to second isolation valve, emergency core cooling system injection lines and related piping;
- A detailed polar crane and a fuel storage rack models developed as part of the project;
- The finite element model of the reduced soil domain to facilitate the integrated DRM SSI analysis in the time-domain.

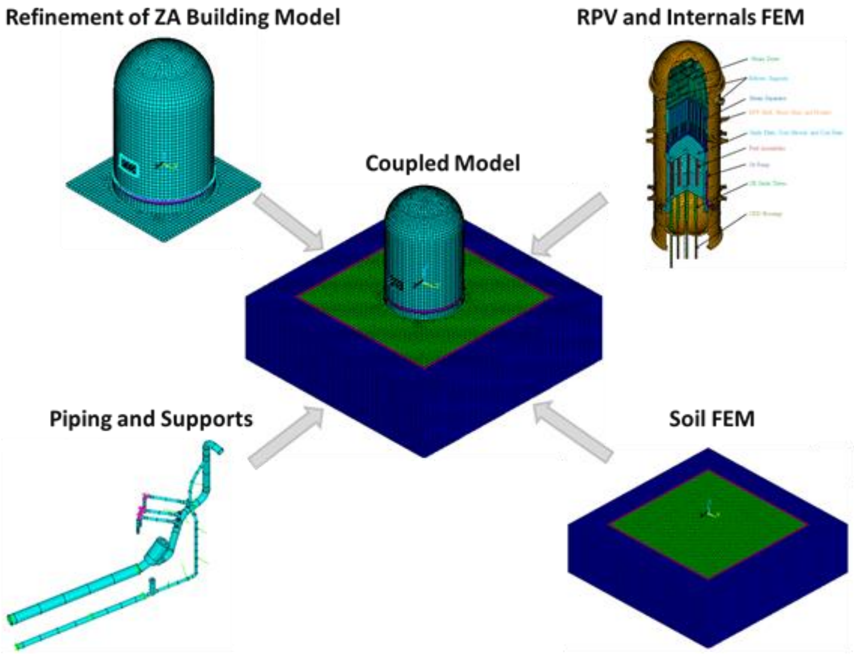

Figure 2. Major components of coupled RB SSI model

The objective of the coupled model analysis is to obtain realistic seismic response for use in the deterministic verification of the selected components including the effects of coupling on the response quantities. This approach also minimizes unintended conservatism of the traditional two-step approach, where the seismic response of the components is obtained separately using the support motion developed in the first step. The coupled analysis solves both steps simultaneously.

- Because the coupled model already represents the safety relevant components, it allows the extraction of component level responses (accelerations, displacements and stresses). The coupled model is developed with sufficient details to fulfil the regulatory requirements, whilst keeping it as simple as possible for optimal usability and maintenance.
- The seismic SSI analysis is performed using the ANSYS (2020) time-domain method. The subsequent stress evaluations are scripted based on the ANSYS (2020) outputs. The capabilities of automation with ANSYS (2020) in combination with own scripting language was also an important aspect for this decision.

In accordance with ENSI-AN-8567 (2014), the seismic SSI analysis considers three (3) soil conditions namely, BE, LB, and UB of the soil stiffness and correlated damping. Each SSI model is evaluated for three (3) sets of ground motion time histories (THs) matching the horizontal and vertical 1E-4 uniform hazard spectra (UHS), which are taken as the RLE. The BE soil condition is defined by the strain compatible shear wave velocities of the subsurface soil layers. The LB and UB soil parameters are taken as the BE soil layer stiffness multiplied by 1.22 and divided by 1.22, respectively. Seismic input motion is represented by horizontal and vertical ground motion response spectra (10^{-4} UHS) characterized by peak ground accelerations (PGA) of 0.35 g, and 0.24 g, respectively. The horizontal 5% damped UHS peaks around 5 Hz with maximum spectral accelerations about 1.1 g.

REVIEW OF DESIGN BASIS STRESS REPORTS OF SSCS

Components of the RPV and RCS are evaluated on the basis of information obtained from a review of existing design basis stress analysis reports such as the following. This important information is developed in coordination with plant engineers and saved in database tables for subsequent use in the seismic evaluations.

- Failure modes associated with structural integrity, function and operability, and stability;
- Material properties;
- Allowable response for the respective failure modes in terms of displacements, tolerance, stresses, forces or moments, buckling limits, local or gross plastic deformations; and
- Normal operating loads and net capacity available to resist seismic demand.

EXTRACTION OF SEISMIC RESPONSE QUANTITIES FOR DETERMINISTIC VERIFICATION

Each of the coupled model seismic analyses cases generates an extensive database of results containing the THs of response displacements and accelerations at nodes, and THs of seismic forces and stress quantities for elements. Post processing of the analysis results extracts response quantities required to perform deterministic verification and to support the following scope:

- Perform deterministic seismic margins analysis of RPV/Internal components and primary cooling system piping and equipment included in the analysis models;
- Determine the potential locations for seismically induced loss of coolant accident (LOCA);
- Develop building seismic response (floor response spectra, FRS) to perform subsequent verifications of components and structures not covered by the models;
- Develop inputs required to perform special analyses to evaluate control rod insertion and fuel element lift-off during seismic events; and
- Determine the effects of coupling on the FRS relative to the standard model.

DETERMINISTIC VERIFICATION OF SELECTED SSCS

In accordance with regulatory guidelines in ENSI-AN-8567 (2014), the coupled model seismic response is used to perform deterministic verification for the RPV, the main RPV internals, including the fuel assemblies and control rods, and the pressurized equipment enclosing the RCS. Figure 3 shows the major components evaluated as part of the verification.

The analysis model is linearized assuming that all gaps are closed and remain closed during the seismic event, and no fuel element lift-off occurs. The resulting response quantities such as stresses in the fuel assembly components used in the deterministic verification are considered to be somewhat conservatively biased.

About 70 items and locations of the RPV, RPV internals and RCS piping and components are evaluated on the basis of response quantities directly extracted from the coupled model seismic analysis. These are identified and discussed briefly in the next sections, while Table 1 presents the controlling failure modes. The evaluated seismic margins are generally well in excess of experience-based capacities assigned to the RPV and internals.

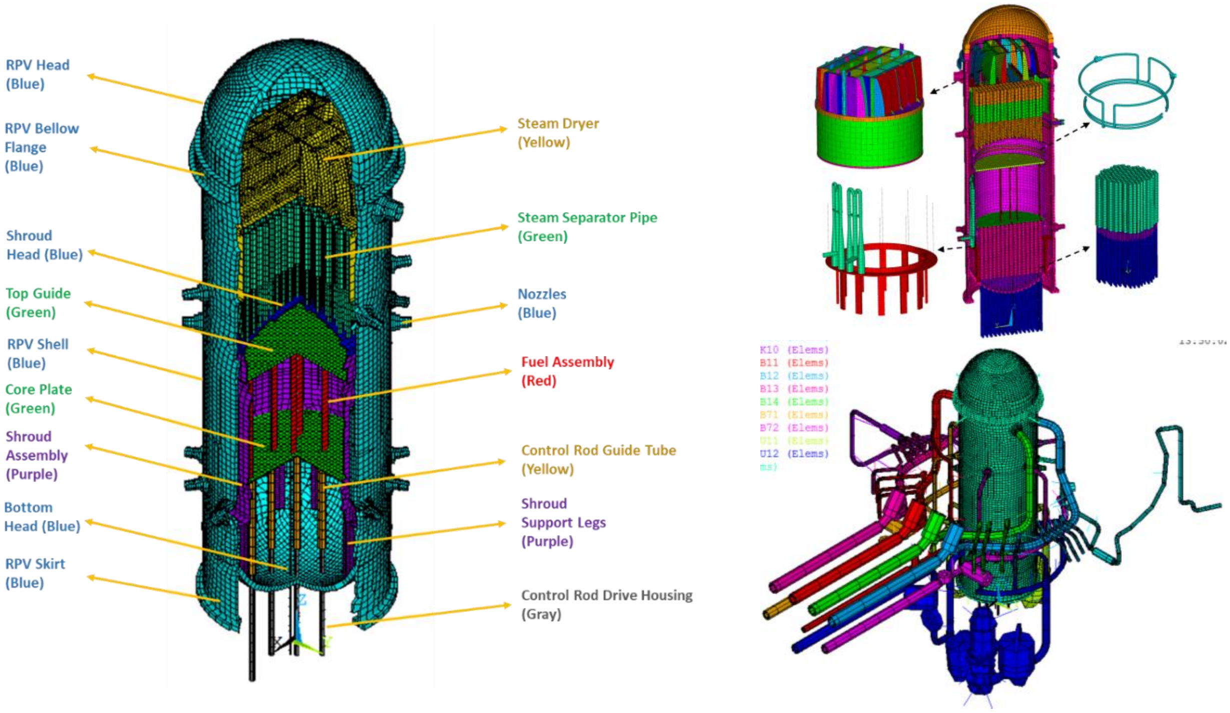

Figure 3. Detailed RPV model (left). RPV model subcomponents (top-right). Detailed piping models (bottom-right)

Table 1: Controlling failure modes

RPV and RCS Components	**Failure Mode**
RPV Shell	Skirt Stress
RPV	Skirt Anchor Bolts
RPV Bottom Head	CRDH Penetrations
RPV Nozzles	Feedwater Piping
Fuel Elements	Spacer Grid
Control Rods	Control Rod Insertion
Shroud Shell	Buckling
Shroud Support Leg	Buckling
Core Plate	Core Plate Ligament
RPV Internal Piping	HPCS&LPCS Piping
RCS Pump	Pump Supports
Refueling Bellows	Supports to Drywell Concrete
Valves	Supports

REACTOR PRESSURE VESSEL AND INTERNALS

Reactor Pressure Vessel Enclosure and Support Skirt

RPV shell components are typically evaluated for primary membrane stresses (Pm) and primary membrane plus bending stresses (Pm+Pb). Table 2 shows the evaluated components of the RPV enclosure against the Pm/Pm+Pb failure. The results of the seismic verification illustrate that the RPV shell is relatively robust and exhibits significant seismic margins relative to RLE. Among the RPV enclosure components, the refuelling bellows exhibit the smallest seismic margins.

Table 2: Evaluated components of RPV enclosure

Description	Description	Description
Bottom Head Penetration	Vessel Flange	Recirculation Outlet Nozzle
Bottom Head	RPV Flange	Recirculation Inlet Nozzle
Bottom Head Ring	Top Head	Steam Outlet Nozzle
RPV Shell	Refuelling Bellow Support	Feedwater Nozzle
RPV Skirt	Refuelling Bellow Lower Flange	HPCS/LPCS Nozzle
RPV Skirt Flange		

RPV Internals Components

Table 3 shows the evaluated components of the RPV internal against the Pm/Pm+Pb failure unless otherwise noted (i.e., buckling). The normal operating load stresses for the internal components is in part due to dead load and in part due to operating condition differential pressure across the shroud support plates which also support the jet pumps. These are obtained on the basis of existing stress reports. Among the internal components in Table 3, the control rod guide tube (CRGT) buckling exhibits the smallest seismic margins. Among the internal piping components, high pressure cooling system (HPCS) & low pressure cooling system (LPCS) piping exhibit the smallest seismic margins.

Table 3: Evaluated components of RPV internal

Description	Description	Description
Shroud Support Leg Buckling	Incore Guide Tube	Shroud Head Dowel Shear
Shroud Support Plate	Shroud Shell Buckling	Steam Separators to Dome Weld
Shroud Support Cylinder	Shroud Wedge Stress	Steam Dryer
CRDH below Penetration	Defl. b/w Shroud & Jet Pump	Steam Dryer Lugs
CRDH at Vessel Penetration	Defl. b/w Shroud & RPV Shell	Steam Dryer Hold Down Buckling
CRDH above Penetration	Core Plate Stiffener Plate Buckling	Jet Pump
CRD Housing Defl. at Penetration	Core Plate Stiffener Plate	LPCI Piping
Incore Housing	Core Plate Ligament Buckling	HPCS & LPCS Piping
CRGT Tube	Core Plate Ligament	Feedwater Sparger
CRGT Base Flange	Top Guide Grid Beam	Steam Dryer Lugs
Buckling of CRGT	Shroud Head	

Anchor Bolt Connections at Selected RPV Locations

The RPV is supported by means of 120 anchor bolts. In addition, RPV flange bolts and shroud head flange bolts are also evaluated. Minimum seismic margin for the anchor bolts is obtained based on the seismic forces obtained from the coupled model analysis.

Atrium 11 Fuel Assembly and Components

The detailed model of the RPV and internals represents the fuel rods and the fuel channel as beam elements connected to each other at by rigid link elements at nine (9) locations representing the spacer grids. The beam elements are assumed to be fixed at the lower core plate and restrained in the horizontal directions at the top core grid. Because the model is linearized, it does not account for potential lift-off of the fuel assemblies, gaps between the spacer grids and the fuel channel and the nonlinear load displacement characteristic grids. The resulting forces and accelerations are somewhat conservatively biased. The acceleration time histories and the FRS developed at the core plate and the upper core guide are suitable for a detailed non-linear analysis of the fuel assemblies, diffuser pumps, etc.

The seismic evaluation addresses the following failure modes:

- Structural integrity of the fuel assemblies, spacer grids and fuel guard;
- Fuel element lift-off; and
- Control rod insertion.

Fuel Assembly Structural Integrity

The safety factors for the fuel channel are obtained at two (2) elevations, one just above the core plate where the core pressure on the fuel channel is maximum and a second at mid-height where the seismic stress is maximum. The seismic margins for the fuel channel and the components of the fuel assembly are all greater than 1.0 for the RLE ground motion. This demonstrates that the fuel assemblies maintain their function during the RLE event with sufficient margin relative to the RLE ground motion.

Fuel Element Lift-off

The fuel element lift-off is evaluated for the uplifting forces (pressure differential due to core flow and RLE) and the weight of the fuel assembly. Once the fuel element is lifted-off, the distance moved is calculated by integrating the Newton's second law equation. It is conservatively assumed that the seismic loads continue to act after the lift-off.

Under the combined forces for Service Level D (ASME, 2009), the net vertical upward acceleration time history, and the allowable lift-off displacement, a safety factor for lift-off is estimated to be greater than 1.0. Thus, the lower tie plate/transition piece remains engaged within the orifice fuel support during RLE seismic event.

Control Rod Insertion

The control rod (CR) insertion function could be compromised if the horizontal deformations of the fuel channels are excessive. As demonstrated above, the fuel assembly and the lower transition piece are predicted to remain engaged within the fuel supports under combined loads. Consequently, no lateral displacement of the lower end of the fuel assembly is predicted. Additionally, the stresses in the fuel channel are also within acceptable limits, and the corresponding maximum seismic displacements of the fuel assembly due to RLE are relatively small.

The fuel assembly deformations relative to the core plate in the above table are evaluated for the fuel assembly near the RPV centerline as these are expected to be governing for CR insertion.

The following reported data substantiate that the CR insertion function is un-compromised for the RLE:

- Tests on control rod insertion capability for BWR fuel assembly (Kiss and Gerber, 1979) demonstrate successful insertion at displacements in excess of 62.5 mm.
- The experience at Kashiwazaki-Kariwa showed that no abnormality was evidenced with respect to control rod insertion at a PGA of about 0.6 g.
- Full-scale test performed by Japan nuclear energy safety organization (JNES) concluded that displacements of the fuel assembly of 83 mm do not affect the insertion time significantly.

Based on these reported performances of CR mechanism, the deterministic capacity for rod insertion is taken to be 40 mm. Thus, the corresponding deterministic seismic margin is greater than 1.0.

PRIMARY COOLING SYSTEM PRESSURE BOUNDARY PIPING

The seismic stresses and support reactions extracted from the coupled model analysis include inertial effects as well as the effects due to seismic anchor motion (SAM). The evaluation reported here assumes both of these as primary response quantities.

Pressure Boundary Piping

The locations in the piping runs at which LOCA could be initiated are taken to be those at which the highest usage factors are reported in the existing stress reports. These typically include elbows, tee junctions, weld seams and reducers. The representative seismic margins are developed accounting for the normal operating stresses at these locations, which are primarily due to dead load and internal pressure.

Seismic margins are obtained for the following piping runs inside containment represented in the coupled model:

- Reactor coolant pressure boundary piping;
- Main steam (MS) system piping and relief valve discharge lines from the MS safety relief valves to the seismic restraints;
- Feed water system piping;
- High pressure core injection systems (HPCIS); and
- Low pressure core injection systems (LPCIS).

The calculated seismic margins for pressure boundary piping are well in excess of 1.0 illustrating that breach of the piping pressure boundary that could result in potential seismic induced LOCA is very unlikely. The smallest seismic margin occurs in the feed water line elbow just upstream of the risers.

KEY EQUIPMENT INSIDE CONTAINMENT

Selected key equipment inside containment incorporated into the coupled model includes in-line components of the pressure boundary piping connected to the RPV, the polar crane, the upper pool fuel storage racks and the steel containment shell. The deterministic verification for these components considers the critical failure modes, materials of construction and allowable stress limits.

In-Line Components of Pressure Boundary Piping

The calculated seismic margins for the selected in-line components (main steam isolation valve [MSIV], safety relief valve [SRV], RCS pump, suction valve, discharge valve) illustrate that these are generally rugged. Because these components are active mechanical items, the allowable stresses are taken as Level B stress limits as described in the KTA 3211.2 (2012) for operability.

Polar Crane

The polar crane is explicitly represented in the coupled model allowing the extraction of stresses associated with the RLE. The polar crane is supported by total of eight (8) wheels at the circular steel girder on the steel containment. Because details related to seismic restraints could not be sufficiently represented in the coupled model, this item is subsequently analysed for the support motion.

Upper Pool Fuel Storage Racks

A sufficiently detailed model of fuel storage rack is represented in the RB coupled model. The rack model represents the total mass and stiffness of the racks as well as the contributing hydrodynamic mass. Non-seismic loads include the dead load and effects of water mass. The stresses due to RLE loads are obtained by scaling the design basis stresses using the ratio of the RLE and the SSE accelerations.

The fuel assemblies are stored in the vertical orientation in individual storage compartments. Each fuel assembly is laterally supported at the top through the upper tie plate which rests against the rack. The racks are designed to maintain the fuel in a specified geometry.

The fuel racks are typically unanchored and free-standing. However, they are laterally braced at the upper pool floor level. They are provided by struts at several levels over the height which is gapped by distance to the adjacent pool walls. As the racks are free to slide on the pool floor, the seismic margin is evaluated assuming the sliding limit equal to the gap between the rack struts and the pool wall. If this gap is closed, it is assumed that the resulting impact leads to failure by compromising the design geometry.

Approximate displacement from sliding is evaluated based on ASCE 43-05 Appendix A (2015) by assuming that fuel rack will act as an unanchored rigid body. Coefficient of friction between steel to wet concrete is conservatively taken as 0.6. After an iterative process, peak vertical acceleration that is used for estimating the effective friction coefficient is calculated which resulted in a seismic margin greater than 1.0.

Steel Containment Vessel

The deterministic verification of the containment shell considers the following failure modes:

- Undisturbed containment shell;
- Stiffener rings;
- Anchorage to the foundation concrete;
- Penetrations openings; and
- Openings for hatches and air locks.

CONCLUDING REMARKS AND INSIGHTS

The regulatory guidelines in ENSI-AN-8567 (2014) state that the RPV and components of the RCS should be evaluated using the coupled model seismic response. This accounts for the expectation that the predicted seismic demand on systems and components (e.g., FRS) in the building is more realistic and includes effects of coupling between the building and the supported heavy equipment.

The results of the evaluation are reported here as seismic margins quantified as the ratios of the net allowable stresses to the stresses due to the seismic stresses obtained from the coupled model SSI analysis. The evaluation demonstrates that all the selected RPV internal components and branch line components in general exhibit seismic margins well in excess of 1.0.

The evaluation demonstrates a robust performance of the RPV internal systems including fuel assembly integrity, seismic deformations of internal components, control rod insertion and fuel element lift-off. The deterministic verification of the RPV and internal components, the primary cooling system pressure boundary piping and selected key equipment including the steel containment shows that all of the components evaluated exhibit a sufficient seismic margin over and above the RLE ground motion.

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