



PRELIMINARY SEISMIC FRAGILITY ANALYSIS OF SELECTED HEAVY COMPONENTS IN LNNP UNIT 1 REACTOR BUILDING

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ABSTRACT

The paper studies the fragility of heavy components in Leningrad Nuclear Power Plant unit 1 reactor building. The analyzed components are: (1) drum separators (4 pcs); (2) main coolant pumps (8 pcs); (3) suction headers (2 pcs); (4) pressure headers (2 pcs); (5) refuelling machine (1 pcs). The reactor stack was excluded from the analysis based on the study of structural drawings of reactor stack and supporting metal structures. It was judged that the multitude (1693 pcs) of channels in reactor core and adjacent small bore piping (50 mm and 70 mm) forms a structure, which inherently has seismic capacity and damping. The fragility of a component is defined as the conditional probability of its failure given a value of the response parameter, such as stress, moment, and spectral acceleration, peak ground acceleration [1]. Using the lognormal-distribution assumption, the fragility (i.e., the probability of failure, f) at any nonexceedence probability level Q can be derived as

$$f^* = \Phi[(\ln(a/\underline{A}) + \beta_U \Phi^{-1}(Q))/\beta_R]$$

where $Q = P(f < f^*|a)$ is the probability that the conditional probability f is less than f^* for a peak ground acceleration a . \underline{A} is the median ground acceleration capacity, β_R is the logarithmic standard deviation representing the inherent randomness about A , and β_U is the logarithmic standard deviation representing the uncertainty in the median value. The quantity $\Phi(\cdot)$ is the standard Gaussian cumulative distribution function, and $\Phi^{-1}(\cdot)$ is its inverse. The stress resultant responses for the investigated heavy component supports are evaluated for drum separator, main coolant pump, suction header, pressure header, and refueling machine. For the purpose of defining fragility curves, the possible failure modes must be identified and evaluated. The results of the fragility analysis are the parameters A , β_U , β_R for selected heavy components.

KEY WORDS: fragility of heavy components, drum separators, main coolant pumps, suction headers, pressure headers, refueling machine, fragility of a component, conditional probability, lognormal-distribution assumption, probability of failure, nonexceedence probability, logarithmic standard deviation, inherent randomness, uncertainty in the median value, standard Gaussian cumulative distribution function, stress resultant responses, failure mode.

INTRODUCTION

This report describes the fragility analysis of five heaviest components of the LAES Main Coolant Circuit (MCC) excluding reactor itself. The analyzed components are: (1) drum separators (4 pcs); (2) main coolant pumps (8 pcs); (3) suction headers (2 pcs); (4) pressure headers (2 pcs); (5) refueling machine (1 pcs). The reactor stack was excluded from the analysis based on the study of structural drawings of reactor stack and supporting metal structures. It was judged that the multitude (1693 pcs) of channels in reactor core and adjacent small bore piping (50 mm and 70 mm) forms a structure, which inherently has seismic capacity and damping.

STUDY OF PLANT PSA MODEL

Four types of postulated initiating events are investigated: (1) Transients; (2) Loss of coolant accidents; (3) Area events; (4) External events. Ten plant systems are rated in importance in mitigating the consequences of postulated initiating events. The investigated plant systems are: (1) Service water system (SWS); (2) Emergency power supply system (EPSS); (3) Emergency feed water system (EFWS); (4) Intermediate Cooling Circuit for Emergency Feed Water System (EFWS ICC); (5) Emergency Steam Condensation System (ESCS); (6) Auxiliary Feed Water System (AFWS); (7) Intermediate Cooling Circuit for Auxiliary Feed Water System (AFWS ICC); (8) Blow Down and Cooling of Reactor System (BCRS); (9) Main Feed Water System (MFWS); (10) Unsalted Water Service System (UWSS). In Figure 1 the relative importances of various systems mitigating postulated initial events are given.

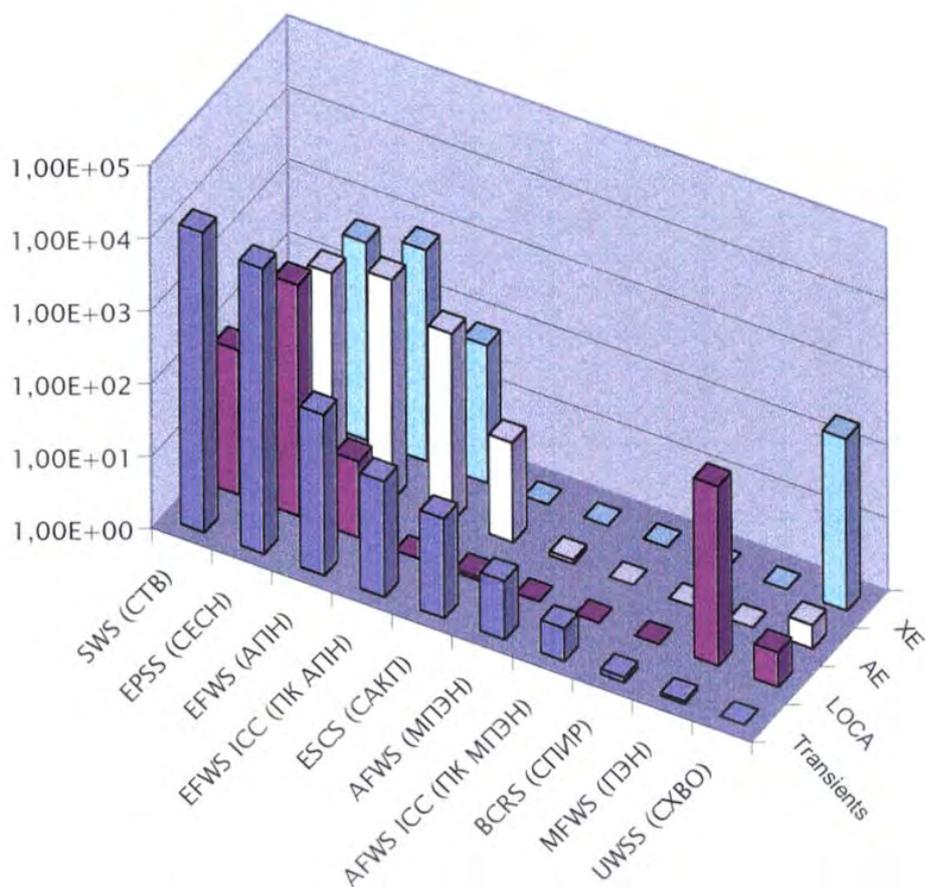


Figure 1 Relative importance's of various systems mitigating postulated initial events

PROCEDURES OF THE SEISMIC FRAGILITY EVALUATION

The description of the procedures of seismic fragility assessment follows reference [1]. The fragility of a component is defined as the conditional probability of its failure given a value of the response parameter, such as stress, moment, and spectral acceleration, peak ground acceleration. The first step in generating fragility curves like those in Figure 1 is to develop a clear definition of what constitutes failure for each component. This definition of failure must be acceptable to both the structural analyst, who generates the fragility curves, and the systems analyst, who must judge the consequences of a component's failure in estimating plant risk. It may be necessary to consider several modes of failure (each with a different consequence), and fragility curves are required for each mode.

Component fragility, which is defined as the conditional probability of failure for a given value of the response parameter, is calculated by developing the probability distribution of the seismic capacity of a component and finding the probability for this capacity being less than the response parameter value.

The fragility of a component is expressed as the conditional probability of failure for a given peak ground acceleration. Data on seismically induced fragilities are generally not available for equipment and structures. Fragility curves must therefore be developed primarily from analysis supplemented with engineering judgment and limited test data. In view of this, maximum use is made of the response - analysis results obtained at the plant design stage. The component fragility for a particular failure mode is expressed in terms of the ground-acceleration capacity A . The fragility is therefore the probability at which the random variable A is less than or equal to a specified value, a . The ground-acceleration capacity is, in turn, modeled as

$$A = A \varepsilon_R \varepsilon_U \tag{1}$$

where A is the median ground - acceleration capacity, ε_R is variable (with unit median) representing the inherent randomness about A , and ε_U is a random variable (with unit median) representing the uncertainty in the median value. It is assumed that both ε_R and ε_U are log-normally distributed with logarithmic standard deviations β_R and β_U , respectively.

Using Equation (1) and the lognormal-distribution assumption, the fragility (i.e., the probability of failure, f) at any nonexceedence probability level Q can be derived as

$$f' = \Phi[(\ln(a/A) + \beta_U \Phi^{-1}(Q)) / \beta_R] \quad (2)$$

where $Q = P(f < f'|a)$ is the probability that the conditional probability f is less than f' for a peak ground acceleration a . The quantity $\Phi(\cdot)$ is the standard Gaussian cumulative distribution function, and $\Phi^{-1}(\cdot)$ is its inverse. For displaying the fragility curves, the nonexceedance – probability level Q is used. Subsequent computations are made easier by discretizing the probability distribution of probability, Q , into values q_i associated with different values of the failure probability f . A family of fragility curves, each with an associated probability q_i , is developed.

SELECTION OF COMPONENTS FOR RESPONSE AND FRAGILITY EVALUATION

The selection of components or systems for fragility evaluation is an iterative process and calls for a close interaction between the systems analyst and the structural analyst. The systems analyst provides a list of structures, systems, and components whose failure may lead to radiological consequences. He may be guided in this selection by the accident sequences identified for the internal events. For a typical nuclear plant, this list may include from about 30 up to 100 classes of components, depending on the detail employed in the plant-system and sequence analysis. The structural analyst develops the response probability distributions and fragility curves for significant failure modes for each of these structures, systems, and equipment. After reviewing plant design criteria, stress reports, and equipment-qualification reports and performing a walk-through inspection of the plant, he may add to, or delete from, the list of components.

EQUIPMENT MODELLING

The layout of heavy equipment is described in the following two Figures. Figure 2 depicts the cross-section of the reactor building. The number notation in Figure 2 has following meaning: (1) Reactor core; (2) Metal support structure (“C” Scheme); (3) Fuel channel lines; (4); Water protection (“L” Scheme); (5) Main circulation pump; (6) Re-fueling Machine; (7) Drum - separator; (8) Upper biological shield (“E” Scheme); (9) Lower biological shield (“OR” Scheme); (10) Side biological shield (“Kzh” Scheme); (11) Lower water lines (LWL); (12) Steam-water lines (SWL); (13) Upper plate (“G” Scheme); (14) Plate covering. The specifications for equipment geometry and material properties for heavy equipment pieces have been obtained from the following two references [2] and [3].

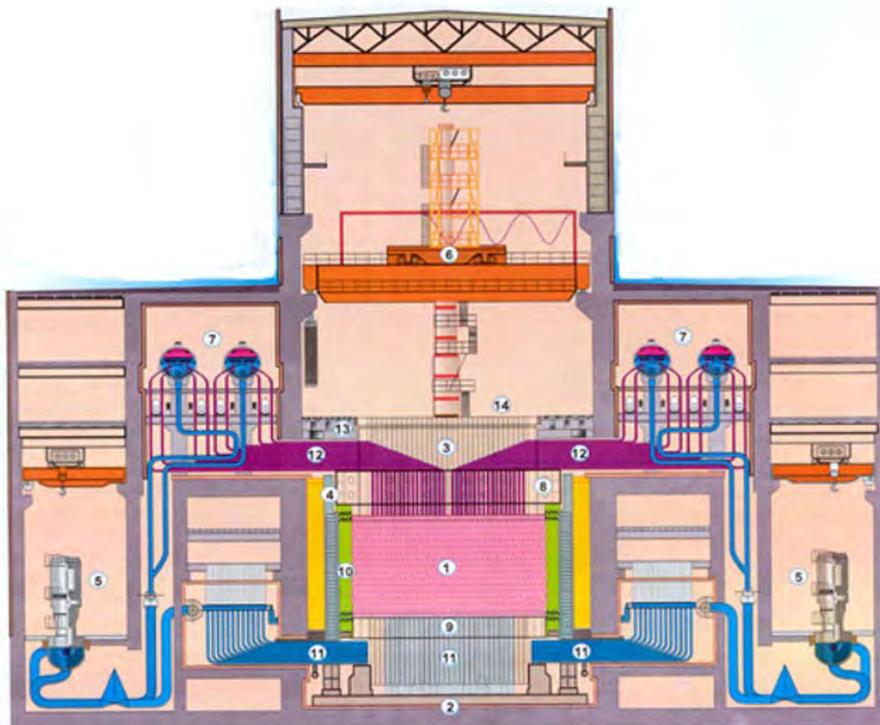


Figure 2 Cross-section of equipment layout in LAES reactor building

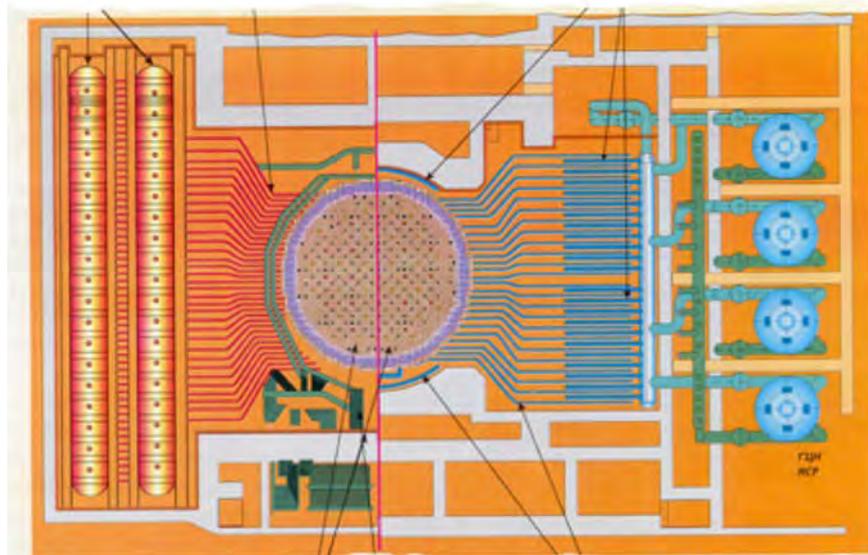


Figure 3 Equipment layout in two typical elevations (+14.40 left) and (+0.00 right) in LAES reactor building
COOLANT CIRCUIT MODEL AND JOINT EQUIPMENT AND STRUCTURAL MODEL

The large bore piping and heavy equipment of the main coolant circuit has been modeled explicitly. The reactor has been excluded from the explicit modeling. However, refueling machine and reactor hall crane have been modeled explicitly because of their significant weight and high elevations. The finite element model for the main coolant circuit depicting the 4 drum separators, 48 downcomer pipes, 3 suction headers, 2 pressure leaders and 8 main coolant pumps is depicted in Figure 4. Part of the joint reactor building and main coolant circuit model is depicted in Figure 5.

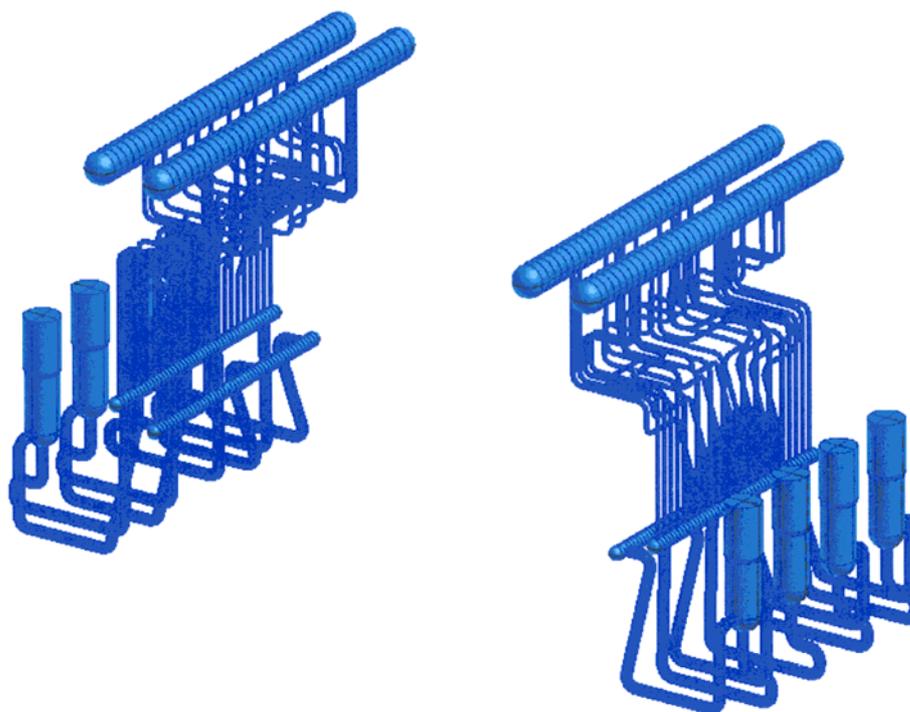


Figure 4 RBMK-1000 reactor main coolant circuit model

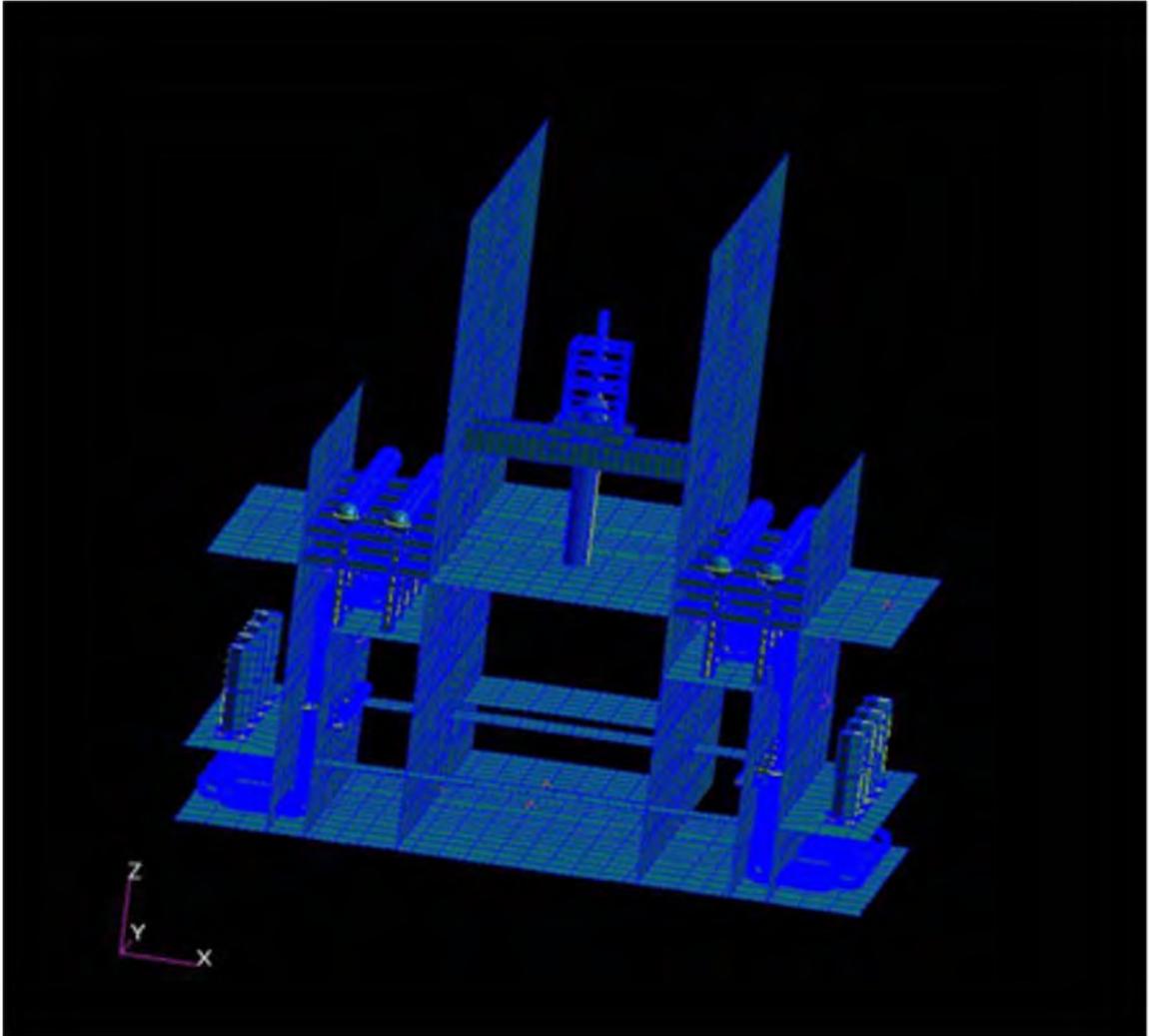


Figure 5 LAES reactor building model merged with coolant circuit and re-fueling machine models

SEISMIC RESPONSE OF HEAVY COMPONENT SUPPORTS

In order to assess the fragility of the heavy components the stress resultant time histories for component supports were calculated using the joint structural-equipment model depicted in Figure 5. The properties of the structural model and the ground motion definition are given in the reference [4]. To determine the most probable failure mode the torsion moment, axial force, shear force and bending moment time histories were calculated for beam elements modeling the component supports. As an example of such stress resultant time history the shear force time history for drum separator support is given in Figure 6.

The length of the time history is 14 seconds. The maximum value of the shear force is 9 meganewtons. The unit for gridlines in y-axis in Figure 6 is 2 meganewtons and the unit for gridlines in x-axis is 2 seconds. As it can be seen from shear force time history the maximum value occurs after 8 seconds from the beginning of the history and its duration short and of the order 0.1 second.

The general shape of the time histories for other stress resultants is the same as for shear force. The maximum values occur after 8 seconds from the beginning of the time history. The number of the high peaks is from three to six and their duration is of the order of 0.1 seconds.

FRAGILITY EVALUATION FOR DRUM SEPARATORS, FOR REFUELING MACHINE AND MAIN COOLANT PUMPS

The drum separator is resting on saddles which are supported to the elevation via seven steel columns. The steel columns are braced in two elevations with horizontal steel beams. Based on this review, it can be concluded that the drum separator support system, including the effect of the main coolant circuit piping, has a low seismic capacity. For the purpose of defining fragility curves, the possible failure modes must be identified and evaluated. The failure mode of drum separator is the interactive failure of shear and bending at the support column head cross – section. The failure

mode yields following fragility parameters: $A_m = 0.1$; $\beta_R = 0.3$; $\beta_U = 0.5$. The fragility curves for drum separators are given in Figure 7.

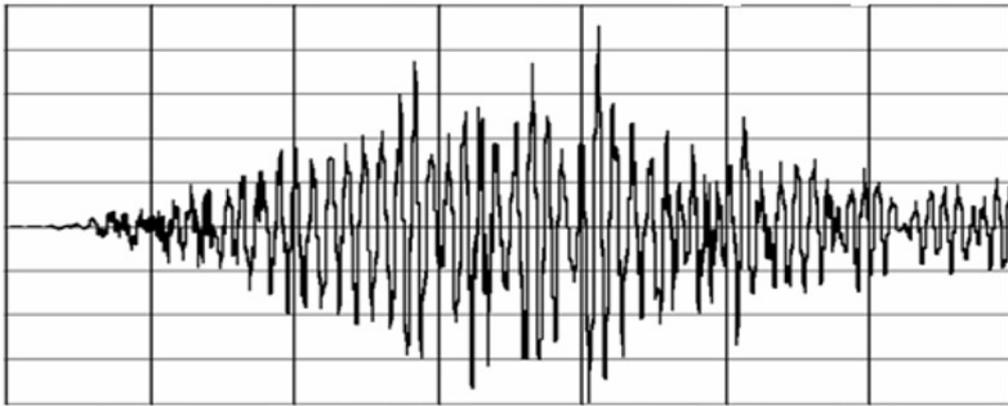


Figure 6 Time history of the shear force of drum separator support. Maximum value 9 MN.

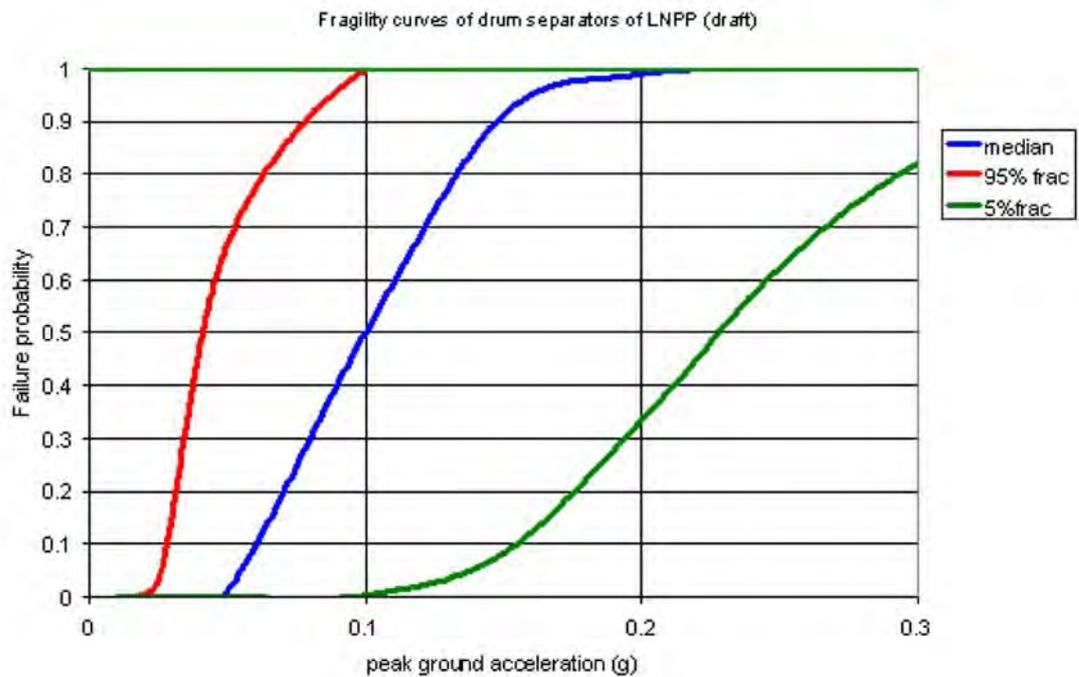


Figure 7 Fragility curves of drum separator

The main coolant pump is resting on support ring, which is supported by the slab of the elevation +0.00. For the purpose of defining fragility curves, the possible failure modes must be identified and evaluated. The failure mode of main coolant pump support is shear failure of the support ring. The shear area of the support ring is 0.75 m^2 . The shear caused by earthquake is 90 MN or three times the maximum shear of three support consoles assumed in modeling. The seismic shear stress for 0.1 g earthquake in the ring is 120 MPa and the yield in shear is 240 MPa. Consequently, the failure mode yields following fragility parameters: $A_m = 0.20$; $\beta_R = 0.2$; $\beta_U = 0.3$. The fragility curves for main coolant pumps are given in Figure 8.

Refueling machine is very high tower type structure resting on trolley which supported on two steel beams spanning the reactor hall at elevation +31.5. The failure mode of the refueling machine is the interactive shear – bending failure of the trolley beams because of overturning effect of refueling machine tower. The fully plastic moment of the beam section between re-fueling machine carriage and re-fueling container is 35 MNm, which is the same value as the seismic max bending moment in the beam. Consequently, the bending failure mode yields following fragility parameters for refueling machine: $A_m = 0.1$; $\beta_R = 0.2$; $\beta_U = 0.3$. The fragility curves of re-fueling machine are given in

Figure 9. The suction and pressure headers are supported on support consoles, which are supported to the wall at $X = \pm 20.7$. The failure mode of suction and pressure headers support consoles is the shear failure of the console cross-section web plate. The shear demand from 0.1g earthquake is 2.5 MN per one support console and the shear capacity of the console is 15 MN. Consequently, the failure mode yields following fragility parameters for both headers: $A_m = 0.60$; $\beta_R = 0.2$; $\beta_U = 0.3$.

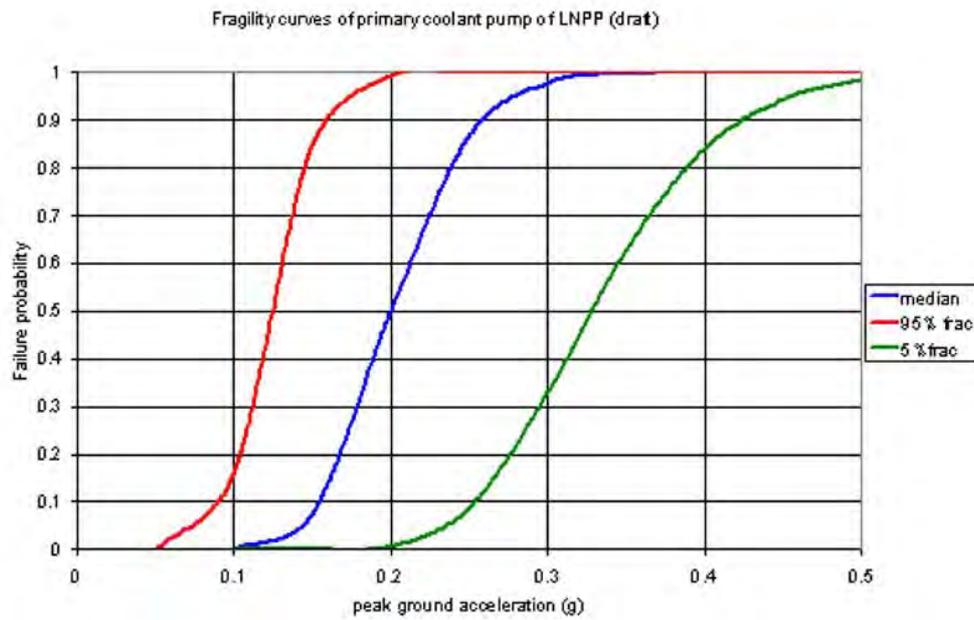


Figure 8 Fragility curves of main coolant pump

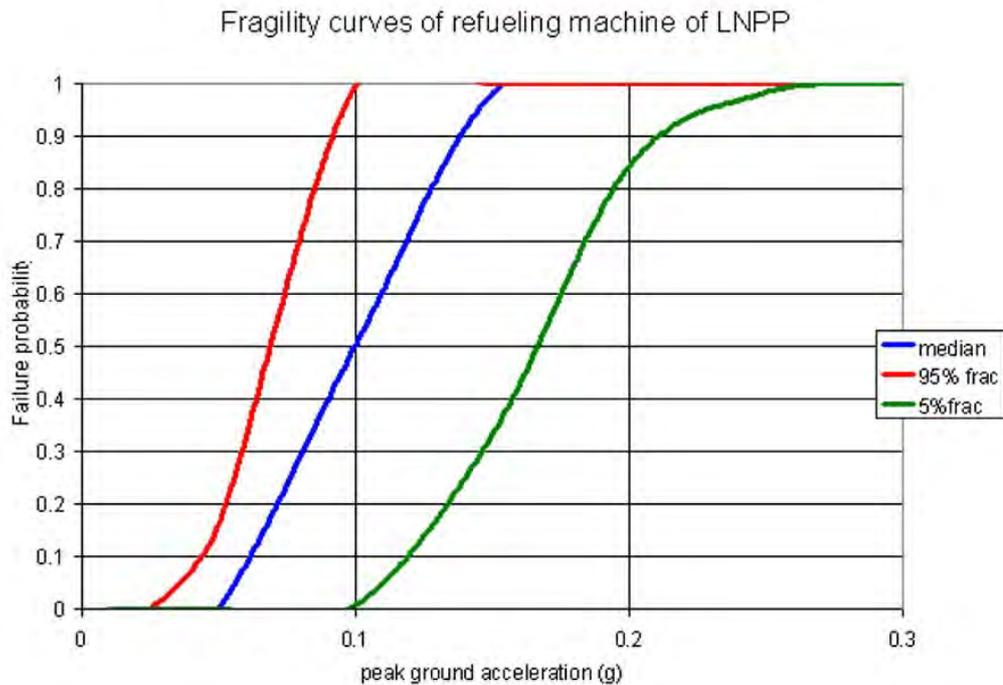


Figure 9 Fragility curves of the refueling machine

CONCLUSION

The main coolant circuit is explicitly modeled and merged with the structural model of the reactor building. The structural response of the five heaviest equipment items is determined. The failure modes of (1) drum separators; (2) main coolant pumps; (3) suction header; (4) pressure header and (5) refueling machine are identified. The fragility parameters using the double lognormal fragility model are determined and the failure curves in median values and 5% and 95% fractile values are plotted for drum separators, main coolant pumps and re-fuelling machine.

It should be noted that the modeling of the equipment supports is based on the schematically presented drawings given in references [2] and [3]. Consequently, the values given for fragility parameters should be understood as preliminary values, which stand for re-evaluation when more accurate specifications for equipment supports are available.

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