FRAGILITY ANALYSIS OF THE REACTOR STEEL SHAFT DOOR DUE TO ACCIDENTAL EXTREME OVERPRESSURE

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Abstract. *This paper describes the probabilistic nonlinear analysis of the hermetic steel door of the reactor shaft failure due to extreme pressure and temperature. The probabilistic assessment of NPP structures for Probabilistic Safety Analysis (PSA2) level 2 of VVER 440/213 in the case of the technology accidents is presented. The scenario of the hard accident in nuclear power plant (NPP) and the methodology of the calculation of the fragility curve of the failure overpressure using the probabilistic safety assessment PSA 2 level is presented. The nonlinear deterministic and probabilistic analysis based on the response surface method (RSM) were considered.*

Keywords

Ansys, fragility, hermetic door, nuclear safety, nonlinear analysis, probability, PSA, RSM, technology accident.

1. Introduction

The IAEA (International Atomic Energy Agency) in Vienna [1] adopted a large-scale project "Stress Tests of NPP", which defines new requirements for the verification of the safety and reliability of NPP due to the accident of NPP in Fukushima. Based on the recommendations of the IAEA in Vienna [1], the probabilistic methodology of the safety and reliability of the NPP structures was accepted for the problem of the safety of the critical structures.

The safety documents of NRC [2], [3] and IAEA [1] initiate the requirements to verify the hermetic structures of NPP loaded by two combinations of the extreme actions. First extreme loads are considered for the probability of exceedance 10^{-4} by year and second for 10^{-2} by year. Other action effects are considered as the characteristic loads during the accident. In the case of the loss-of-coolant accident (LOCA) the steam pressure expands from the reactor hall to the bubble condenser [4]. The reactor and the bubble condenser reinforced structures with steel liner are the critical structures of the NPP hermetic zone [4]. Next, one from the critical technology structures are the reactor hermetic covers and doors.

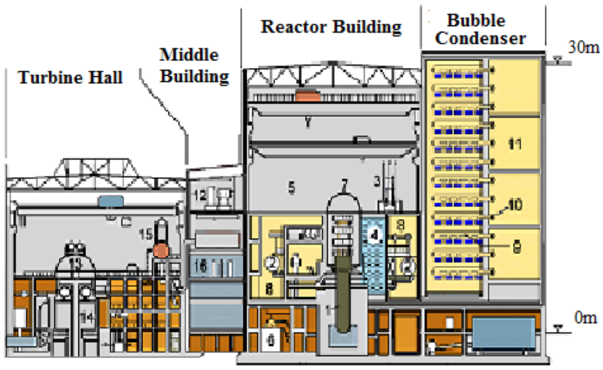

Fig. 1: Section plane of the NPP with reactor VVER440/213.

The NPP with the reactor VVER440 consist of four buildings – reactor building, lengthwise side building, cross side building and turbine hall (Fig.1). The FEM model of the NPP was created in the software ANSYS.

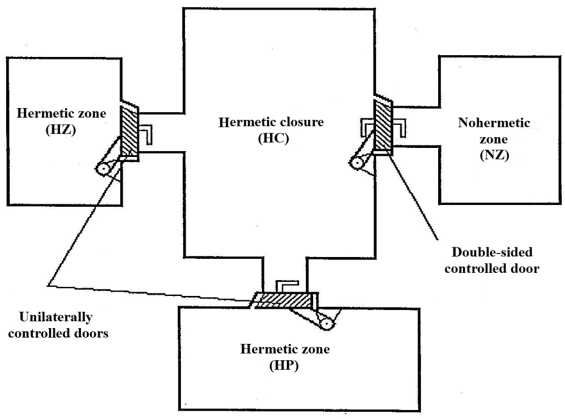

Fig. 2: Scheme of the safety system of the hermetic zone.

On the base of the global analysis of the safety of the NPP structures under the technology accident in accordance with the international standards [1], [5] the detailed analysis of the hermetic cover, protective hood, and doors. The safety scheme of the hermetic doors and the hermetic zone are presented in Fig.2.

The nonlinear analysis and the full probabilistic analysis were used as the input data for the next risk analysis of the NPP structures in accordance with the international standards.

Tab.1: The assumed scenarios of the accidents in the hermetic zone

Type	Duration	Overpressure in HZ [kPa]	Extreme temperatures [ºC]
I.	1hour - 1day	150	127
II.	2hours - 7days	250	150
III.	1year	-	80 - 120

The Commission NRC [2] uses the probabilistic risk assessment (PRA) to estimate risk by computing real numbers to determine what can go wrong, how likely is it, and what are its consequences. Thus, PRA provides insights into the strengths and weaknesses of the design and operation of a nuclear power plant.

For the type of NPP a PRA can estimate three levels of risk:

- A Level 1 PRA estimates the frequency of accidents that cause damage to the nuclear reactor core. This is commonly called core damage frequency (CDF).
- A Level 2 PRA, which starts with the Level 1 core damage accidents, estimates the frequency of accidents that release radioactivity from the nuclear power plant.
- A Level 3 PRA, which starts with the Level 2 radioactivity release accidents, estimates the consequences in terms of injury to the public and damage to the environment.

The definition of the fragility curve of NPP generally represents a crucial step for the level 2 probabilistic safety assessment (PSA2), where the probability of structure failure can be evaluated as the convolution of the fragility curve with the load curve. The assessment of the structural strength of the nuclear power plant has acquired even a greater importance in the framework of post-Fukushima stress tests where the assessment of the safety margin and off-design conditions [6].

2. Scenario of the technology accident

The previous analysis was achieved for the overpressure value of 100kPa due to design basic accident (DBA), which corresponds of the loss of coolant accident due to guillotine cutting of the coolant pipe [4]. When the barbotage tower operates in the partial or zero performance the overpressure is equal to the 150 - 300 kPa. The ENEL propose the maximum temperature in the reactor shaft is equal about to 1.800ºC and in the containment around the reactor shaft is equal about to 350ºC [4]. The possibility of the temperature increasing to the containment failure state is considered in the scenario too.

In the case of the hard accident the overpressure can be increased linearly, and the internal and external temperature are constant. Three types of the scenarios were considered (Tab.1). The critical was the accident during 7 days with the overpressure 250kPa, internal temperature 150ºC and external temperature -28ºC.

3. Calculation model

The technology segments of the NPP hermetic zone are made from the steel. The hermetic steel doors type A262 (with dimension 1600/900/150 mm) are located at the reactor shaft. The steel doors fulfil both the sealing and shielding functions. The technology segments of the NPP hermetic zone are made from the steel (S235).

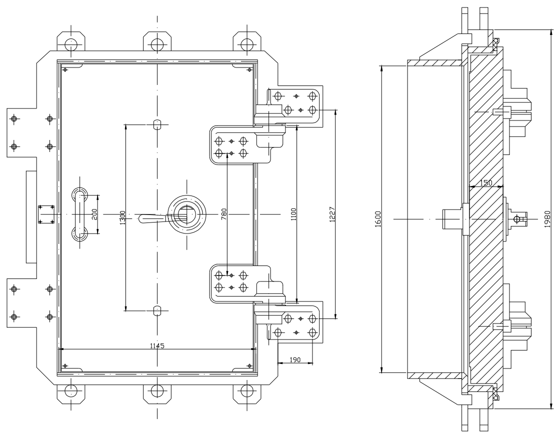

Fig. 3: Scheme of the reactor shaft hermetic door - type A262.

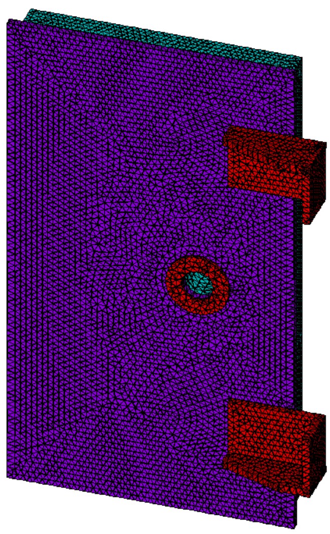

Fig. 4: FEM model of the reactor shaft hermetic door.

The steel door is fitted in the frame cast in concrete and sealed to the frame with double rubber packing of 150 mm in width. The FEM model of the hermetic steel door is shown in Fig.4. The detailed FEM model has 199.469 SOLID185 and CONTA173 elements.

4. Acceptance criteria

In the case of the nonlinear analysis the thermal depended material properties are used following the input data for material 08CH18N10T defined in standard CSN 413240, CSN 411700, CSN 413230, CSN 413240 and NTD SAI Section II. The criterion for the max. stress values is limited by the H-M-H plastic potential [4], [8] and [9]. The failure of the steel structure is limited by the max. strain values or by the stability of the nonlinear solution [10] and [11].

The standard STN EN 1993 1-2 [9] define following characteristic values of the strain for the structural steel :

- yield strain $\varepsilon_{ay,\theta} = 0.02$
- ultimate strain $\varepsilon_{au,\theta} = 0.15$
- max. limit strain $\varepsilon_{ae,\theta} = 0.20$

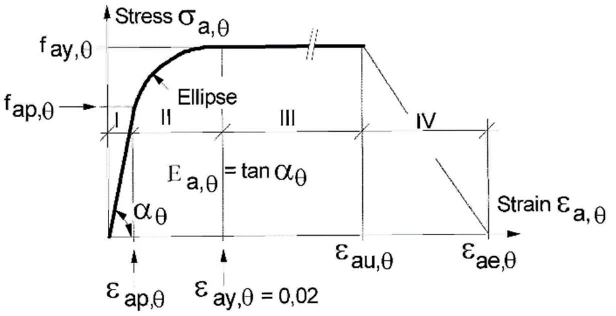

Fig. 5: Stress-strain relationship of the steel dependent on temperature.

The stress-strain relationship for the steel (Fig.5) are considered in accordance with Eurocode [9] and [10] on dependency of temperature level for heating rates between 2 and 50K/min. In the case of the steel the stress-strain diagram is divided on four regions.

The stress-strain relations are defined in following form in region I:

$$\sigma_{a,\theta} = \left(f_{ay} - c\right) + \frac{b}{a}\sqrt{a^2 - \left(\varepsilon_{ay,\theta} - \varepsilon_{a,\theta}\right)^2}\,, \tag{1}$$

$$a^2 = \left(\varepsilon_{ay,\theta} - \varepsilon_{ap,\theta}\right)\left(\varepsilon_{ay,\theta} - \varepsilon_{ap,\theta} + c/E_{a,\theta}\right),$$

$$b^2 = E_{a,\theta}\left(\varepsilon_{ay,\theta} - \varepsilon_{ap,\theta}\right)c + c^2\,,$$

$$c = \frac{\left(f_{ay,\theta} - f_{ap,\theta}\right)^2}{E_{a,\theta}\left(\varepsilon_{ay,\theta} - \varepsilon_{ap,\theta}\right) - 2\left(f_{ay,\theta} - f_{ap,\theta}\right)}\,.$$

and in region III:

$$\sigma_{a,\theta} = f_{ay,\theta}\,. \tag{2}$$

5. Nonlinear analysis

The nonlinear analysis based on potential theory considering the isotropic material properties was made for the solid elements SOLID185 and CONTA173 elements [8] in the FEM model.

The steel is typical isotropic material. The elastic-plastic behaviour of the isotropic materials is described by the HMH yield criterion [8].

Consequently, the stress-strain relations are obtained from the following relations:

$$\{d\sigma\} = \left[D_{el}\right]\left(\{d\varepsilon\} - \{d\varepsilon^{pl}\}\right) = \left[D_{el}\right]\left(\{d\varepsilon\} - d\lambda\left\{\frac{\partial Q}{\partial \sigma}\right\}\right), \tag{3}$$

where $\left[D_{ep}\right]$ is elastic-plastic matrix in the form :

$$\left[D_{ep}\right] = \left[D_e\right] - \frac{\left[D_e\right]\left\{\frac{\partial Q}{\partial \sigma}\right\}\left\{\frac{\partial F}{\partial \sigma}\right\}^T\left[D_e\right]}{A + \left\{\frac{\partial F}{\partial \sigma}\right\}^T\left[D_e\right]\left\{\frac{\partial Q}{\partial \sigma}\right\}}\,. \tag{4}$$

The hardening parameter A depends on the yield function and model of hardening (isotropic or kinematic). Huber-Mises-Hencky (HMH) define the yield function in the form:

$$\sigma_{eq} = \sigma_T\left(\kappa\right), \tag{5}$$

where σ_{eq} is equivalent stress in the point and $\sigma_o\left(\kappa\right)$ is yield stress depends on the hardening.

In the case of kinematic hardening by Prager (versus Ziegler) and the ideal Bauschinger's effect is given

$$A = \frac{2}{9E}\sigma_T^2 H'\,. \tag{6}$$

The hardening modulus H' for this material is defined in the form:

$$H' = \frac{d\sigma_{eq}}{d\varepsilon_{eq}^p} = \frac{d\sigma_T}{d\varepsilon_{eq}^p}\,. \tag{7}$$

When this criterion is used with the isotropic hardening option, the yield function is given by:

$$F\left(\sigma\right) = \sqrt{\{\sigma\}^T\left[M\right]\{\sigma\}} - \sigma_o\left(\varepsilon_{ep}\right) = 0\,, \tag{8}$$

where $\sigma_o\left(\varepsilon_{ep}\right)$ is the reference yield stress, ε_{ep} is the equivalent plastic strain and the matrix [M] is diagonal.

On the base of the elastic-plastic theory and the HMH function of plasticity the extreme strain and stress of the reactor hermetic door for the accident scenario type II were calculated. The matrix [*M*] is defined as follows:

$$[M]=\begin{bmatrix}1&0&0&0&0&0\\0&1&0&0&0&0\\0&0&1&0&0&0\\0&0&0&2&0&0\\0&0&0&0&2&0\\0&0&0&0&0&2\end{bmatrix}. \tag{9}$$

6. Probability nonlinear assessment

The probabilistic methods are very effective to analyze of the safety and reliability of the structures considering the uncertainties of the input data [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22] and [23]. The probability analysis of the loss of the reactor cover integrity was [4], made for the overpressure loads from 250 kPa to 7000 kPa using the nonlinear solution of the static equilibrium considering the geometric and material nonlinearities of the steel shell and beam elements. The probability nonlinear analysis of the technology segments is based on the proposition that the relation between the input and output data can be approximated by the approximation function in the form of the polynomial [7, 8]. The full probabilistic assessment was used to get the probability of technology segment failure.

The safety of the technology segments was determined by the safety function SF in the form [10]

$$SF = E/R \quad \text{and} \quad 0 \le SF < 1\,, \tag{10}$$

where *E* is the action function and *R* is the resistance function.

The reliability function *RF* is defined in the form:

$$RF = g(R,E) = 1 - SF = R - E > 0\,, \tag{11}$$

where $g(R,E)$ is the reliability function.

The probability of failure can be defined by the simple expression:

$$P_f = P[R<E] = P[(R-E)<0]. \tag{12}$$

The reliability function RF can be expressed generally as a function of the stochastic parameters X_1, X_2 to X_n, used in the calculation of *R* and *E*.

$$RF = g(X_1, X_2, ..., X_n)\,. \tag{13}$$

The failure function $g(\{X\})$ represents the condition (capacity margin) of the reliability, which can be either an explicit or implicit function of the stochastic parameters and can be single (defined on one cross-section) or complex (defined on several cross-sections, e.g., on a complex finite element model).

In the case of the nonlinear analysis the correct solution of the elastic-plastic behavior of the structures is determined by the function plasticity. The HMH function of the plasticity was used for the nonlinear solution of the steel technology segments. This plasticity function is defined in the form:

$$R = f_y \quad \text{and} \quad E = \sigma_{ef}\,, \tag{14}$$

where the effective stress σ_{ef} (Von Mises stress) is defined as follows

$$\sigma_{ef} = \left(\frac{1}{2}\left[(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_1)^2 + (\sigma_3-\sigma_1)^2\right]\right)^{\frac{1}{2}}. \tag{15}$$

The failure of the steel technology segments in the frame of the PSA analysis is defined by the ultilimite values of the maximal strain deformation. This failure function is defined in the form:

$$R = \varepsilon_{a\,y,\theta} \quad \text{and} \quad E = \varepsilon_{ef}\,, \tag{16}$$

where the effective strain ε_{ef} (Von Mises strain) is defined as follows

$$\varepsilon_{ef} = \frac{1}{1+\nu'}\left(\frac{1}{2}\left[(\varepsilon_1-\varepsilon_2)^2 + (\varepsilon_2-\varepsilon_1)^2 + (\varepsilon_3-\varepsilon_1)^2\right]\right)^{\frac{1}{2}}, \tag{17}$$

where ν' is the effective Poisson constant.

The failure probability is calculated from the evaluation of the statistical parameters and theoretical model of the probability distribution of the reliability function Z = g(X) using the simulation methods. The failure probability is defined as the best estimation on the base of numerical simulations in the form:

$$p_f = \frac{1}{N}\sum_{i=1}^{N} I\left[g(X_i) \le 0\right], \tag{18}$$

where N in the number of simulations, g(.) is the failure function, I[.] is the function with value 1, if the condition in the square bracket is fulfilled, otherwise is equal 0.

The full probabilistic analysis result from the nonlinear analysis of the series simulated cases considered the uncertainties of the input data.

The various simulation methods (direct, modified or approximation methods) can be used for the consideration of the influences of the uncertainty of the input data [4].

In case of the nonlinear analysis of the full FEM model the approximation method RSM (Response surface method) is the most effective method [8].

The RSM method assumes that it is possible to define the dependency between the variable input and the output data through the approximation functions in the following form:

$$Y = c_o + \sum_{i=1}^{N} c_i X_i + \sum_{i=1}^{N} c_{ii} X_i^2 + \sum_{i=1}^{N-1}\sum_{j>i}^{N} c_{ij} X_i X_j\,, \tag{19}$$

where c_o is the index of the constant member; c_i are the indices of the linear member and c_{ij} the indices of the quadratic member, which are given for predetermined schemes for the optimal distribution of the variables or for using the regression analysis after calculating the response. Approximate polynomial coefficients are given from the condition of the error minimum, usually by the "Central Composite Design Sampling" (CCD) method or the "Box-Behnken Matrix Sampling" (BBM) method [8].

On base of experimental design, the unknown coefficients are determined due to the random variables selected within the experimental region. The uncertainty in the random variables can be defined in the model by varying in the arbitrary amount producing the whole experimental region.

The total vector of the deformation parameters $\{r_s\}$ in the FEM is defined for the sth-simulation in the form:

$$\{r_s\} = \left[K_{GN}\left(E_s, F_\sigma\right)\right]^{-1} \left\{F\left(G_s, Q_s, P_s, T_s\right)\right\}, \quad (20)$$

and the strain vector

$$\{\varepsilon_s\} = [B_s]\{r_s\}, \quad (21)$$

where $[K_{GN}]$ is the nonlinear stiffness matrix depending on the variable parameters E_s and F_σ, F_σ is the HMH yield function defined in the stress components, $\{F\}$ is the vector of the general forces depending on the variable parameters G_s, Q_s, P_s and T_s for the s_{th}-simulation.

7. Uncertainties of the input data

The uncertainties are coming from the following sources [4], [7], [10] and [14]:

- Parameters of material properties. Based on experiments with concrete elements the standard deviation is 11.1%. In case of other materials this value is about 5%.
- Assessment of mechanical characteristics error factors are about 8-12%, it depends on the construction material differences used for the different units with VVER 440/213. In some cases, it can be conservative, in other cases non-conservative impact.
- Uncertainties in the numerical results in the value of 10-15%. In this area we can take into consideration the steel liner with the concrete elements.
- Uncertainties arising from the temperatures impact in the value of 10%.
- Other calculations assumptions 3-5%.

The mean values and standard deviations were defined in accordance of the experimental test and design values of the material properties and the action effects [6 and 8] (see Tab.3). Based on the results from the simulated nonlinear analysis of the technology segments and the variability of the input parameters 10^6 Monte Carlo simulations were performed in the system ANSYS [8].

Tab.2: Variability of input parameters.

Quantity	Charact. value	Variable	Type	Mean μ	Deviat σ[%]	Min. value	Max. value
Material							
Strength	F_k	f_{var}	N	1.10	6.6	0.77	1.35
Action effects							
Dead load	G_k	g_{var}	N	1	5	0.81	1.20
Live load	Q_k	q_{var}	GU	0.64	22.6	0.23	1.36
Pressure LOCA	p_k	p_{var}	N	1	8	0.70	1.33
Temperature	T_k	t_{var}	GU	0.67	14.2	0.40	1.15
Model uncertainties							
Action	E_k	e_{var}	N	1	5	0.81	1.19
Resistance	R_k	r_{var}	N	1	5	0.81	1.20

8. Probability nonlinear analysis of the reactor door

The calculation of the probability of the reactor door failure is based on the results of the nonlinear analysis for various level of the accident pressure and mean values of the material properties. The critical area of the technology segments defined from the nonlinear deterministic analysis are the mechanical closures. The CCD method of the RSM approximation is based on 45 nonlinear simulations depending on the 6 variable input data. The nonlinear solution for the one simulation consists about the 50 to 150 iterations depending on the scope of the plastic deformations in the calculated structures. The sensitivity analysis gives us the information about the influences of the variable properties of the input data to the output data. These analyses are based on the correlation's matrixes.

9. Fragility curves of failure pressure

The PSA approach to the evaluation of probabilistic pressure capacity involves limit state analyses [4], [7], [10] and [11]. The limit states should represent possible failure modes of the confinement functions. The containment [4] may fail at different locations under different failure modes. Consider two failure modes A and B, each with n fragility curves and respective probabilities p_i ($i = 1,\ldots, n$) and q_j ($j = 1,\ldots, n$). Then the union $C = A \cup B$, the fragility $F_{Cij}(x)$ is given by

$$F_{Cij}(x) = F_{Ai}(x) + F_{Bj}(x) - F_{Ai}(x) \cap F_{Bj}(x), \quad (22)$$

where the subscripts i and j indicate one of the n fragility curves for the failure modes and x denote a specific value of the pressure within the containment. The probability p_{ij} associated with fragility curve $F_{Cij}.(x)$ is given by $p_i.\ q_j$ if the median capacities of the failure modes are independent. The result of the intersection term in (22) is $F_{Aj}(x)$, $F_{Bj}(x)$ when the randomness in the failure mode capacities is independent and min $[F_{Ai}.(x), F_{Bj}.(x)]$ when the failure modes are perfectly dependent.

The following is and the consequence of an accident depends on the total leak area. Multiple leaks at different locations of the containment (e.g., bellows, hatch, and airlock) may contribute to the total leak area. Using the methodology described above, we can obtain the fragility curves for leak at each location.

For a given accident sequence, the induced accident pressure probability distribution, $h(x)$, is known. This is convolved with the fragility curve for each leak location to obtain the probability of leak from that location (P_{Li}). It is understood that there is no break or containment rupture at this pressure.

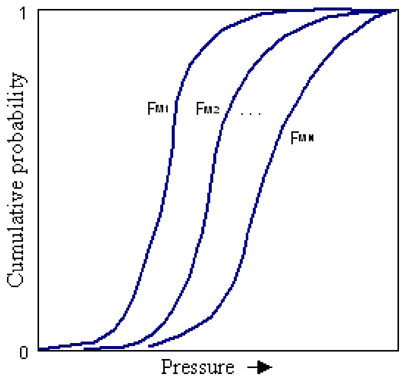

Fig. 6: Family of fragility curves showing modelling uncertainty.

$$p_{Li} = \int_0^\infty h(x)\left[1 - F_b(x)\right] F_l(x)\, dx\,, \tag{23}$$

here $F_b(x)$ is the fragility of break at the location and $F_l(x)$ is the fragility of leak.

The leak is for each location specified as a random variable with a probability distribution.

The probability of reactor cover failure is calculated from the probability of the reliability function RF in the form,

$$P_f = P\,(RF < 0), \tag{24}$$

where the reliability condition *RF* is defined depending on a concrete failure condition

$$RF = 1 - \varepsilon_{ef} / \varepsilon_{a\,y,\theta}\ , \tag{25}$$

where the failure function was considered in the form (16).

The fragility curve of the failure pressure was determined using 45 probabilistic simulations using the RSM approximation method with the experimental design CCD for 10^6 Monte Carlo simulations for each model and 5 level of the overpressure. The various probabilistic calculations for 5 constant level of overpressure next for the variable overpressure for gauss and uniform distribution were taken out. The failure criterion of the steel structures using HMH (Von Mises) plastic criterion with the multilinear kinematic hardening stress-strain relations for the various level of the temperatures and the degradation of the strength were considered.

The uncertainty of the input data (tab.2) and the results of the nonlinear analysis of the technological structures for various level of the accident pressure were taken.

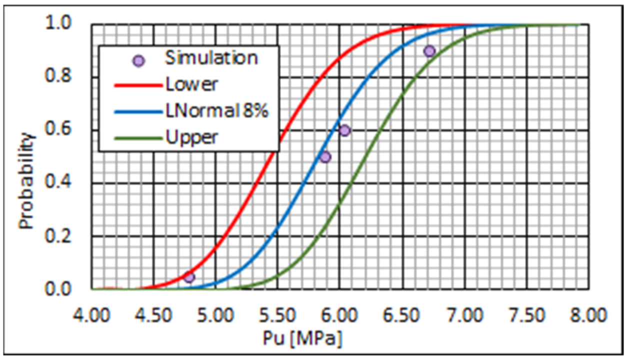

Fig. 7: Fragility curves of the steel reactor shaft door.

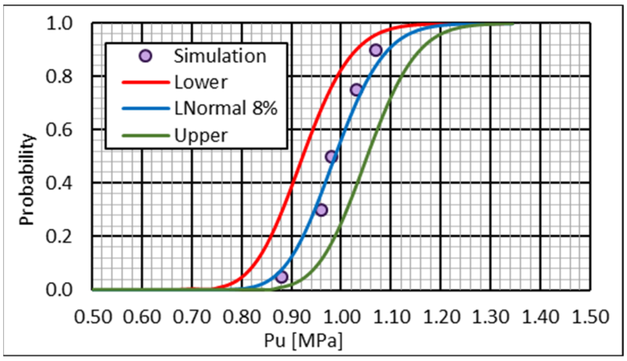

Fig. 8: Fragility curves of the concrete frame about the reactor shaft door.

The idealized fragility curves for the reactor shaft door are presented in Fig.7. In case of the reinforced structure frame about of the door the idealized fragility curves are presented in Fig.8.

10. Conclusion

This report is based on methodology of the probabilistic analysis of structures of hermetic zone of NPP with reactor VVER440/213 detailed described in work [4]. The nonlinear probabilistic analysis of the reactor shaft door failure is in accordance with the requirements IAEA [1] and NRC [2], experiences from the similar analysis NPP in abroad [21], new knowledges from the probabilistic analysis of structures [7], [10], [11], [12], [14] and our experiences from the previous analysis [4].

These analyses go out from the previous results of the monitoring of material properties [4], and NPP structures, as well as from the results of the resistance analysis of the important structural components from the point of the initiated accidents. The structures were analysed on impact of the extreme load's situation defined in the scenarios of the internal accidents.

According to the nonlinear deterministic analysis were defined the most critical structural components for which the values of the failure pressure of the accident are determined on base of the best estimation. We propose from the supposition that the loss of containment integrity occur and the performance of the NPP can be unsafe. The critical elements were identified taking into consideration also uncertainties of the input data in the results.

The nonlinear analysis of the loss of the containment integrity was made for the overpressure loads from 250kPa using the nonlinear solution of the static equilibrium considering the geometric and material nonlinearities of the steel shell and solid elements. The nonlinear analyses were performed in the ANSYS program using the HMH plastic condition [8].

The standard STN EN 1993 1-2 [9] define following characteristic values of the strain for the structural steel - yield strain and ultimate strain.

The probability analysis of the loss of the concrete containment integrity was made for the overpressure loads from 250kPa to 7.000kPa using the nonlinear solution of the static equilibrium. The uncertainties of the loads level (temperature, dead and live loads), the material model of the steel structures as well as the inaccuracy of the calculation model and the numerical methods [4] were considered in the approximation RSM method for CCD experimental design and 10^6 Monte Carlo simulations.

This report is based on the methodology of the probabilistic analysis of structures of the hermetic zone of NPP with reactor VVER44/213 detailed described in the work [4]. The uncertainties of the loads level, the material model of the steel structures as well as the inaccuracy of the calculation model and the numerical methods were considered in the approximation RSM method for CCD experimental design and 10^6 Monte Carlo simulations [7] and [8].

One from the critical technology segments of the containment is the hermetic steel door type A252 with the failure pressure $p_{u.0,05}$ = 4.78MPa. The mean value of pressure capacity of the steel door type A252 is $p_{u.0,50}$= 5.88MPa, the upper bound of 95% is $p_{u.0,95}$= 6.75Ma. These fragility curves (Fig.7, 8) are the input data for the following risk analysis of the NPP.

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