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PROBABILISTIC SAFETY ANALYSIS OF THE NUCLEAR POWER PLANTS IN SLOVAKIA

PROBABILISTYCZNA ANALIZA BEZPIECZEŃSTWA ELEKTROWNI JĄDROWYCH

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Abstract: *This paper gives the results of the safety analysis of the nuclear power plants in Slovakia. The probabilistic assessment of NPP concrete containment and technologically steel segment penetration for Probabilistic Safety Analysis (PSA) level 2 of VVER 440/213 in the case of seismic and LOCA accident is presented. There is showed summary of calculation models and calculation methods for the probability analysis of the structural integrity considering load, material and model uncertainties. The numerical simulations on the base of LHS method were realized in the system ANSYS and FReET. Copyright©2010 Preprint of KONBiN*

Keywords : *Probabilistic Safety; Nuclear Power Plants; LHS; ANSYS; FReET*

Streszczenie: *Artykuł przedstawia wyniki analizy bezpieczeństwa nuklearnych elektrowni na Słowacji. Przedstawiono probabilistyczną ocenę betonowej obudowy bezpieczeństwa elektrowni nuklearnej i przenikania przez stal konstrukcji dla Probabilistycznej Oceny Bezpieczeństwa (PSA) na poziomie 2 wg VVER 440/213 w przypadku wydarzeń sejsmicznych i dla przypadku utraty chłodziwa (LOCA). Artykuł przedstawia w skrócie modele obliczeń i metody obliczeń dla probabilistycznej analizy nienaruszalności strukturalnej uwzględniając obciążenie, materiał i niepewności modelu. Numeryczne symulacje przeprowadzono na bazie metody LHS w systemie ANSYS i FReET. Copyright©2010 Pradruk KONBiN*

Słowa kluczowe: *bezpieczeństwo probabilistyczne, elektrownie nuklearne, LHS; ANSYS; FReET*

1. Introduction

The International Atomic Energy Agency set up a program [1] to give guidance to its member states on the many aspects of the safety of nuclear power reactors. The general purpose of the probability analysis of the containment integrity [1, 9] was to define the critical places of the structure elements and to estimate the structural collapse. Following the results from Loss of Coolant Accident (LOCA) scenarios the probability check of the structural integrity may be realized for the random value of the loads and the material properties by modified LHS method [8]. For a complex analysis of the concrete structure for different kind of loads, ANSYS software and the program CRACK (created by Králik) [5, 6] were provided to solve this task.

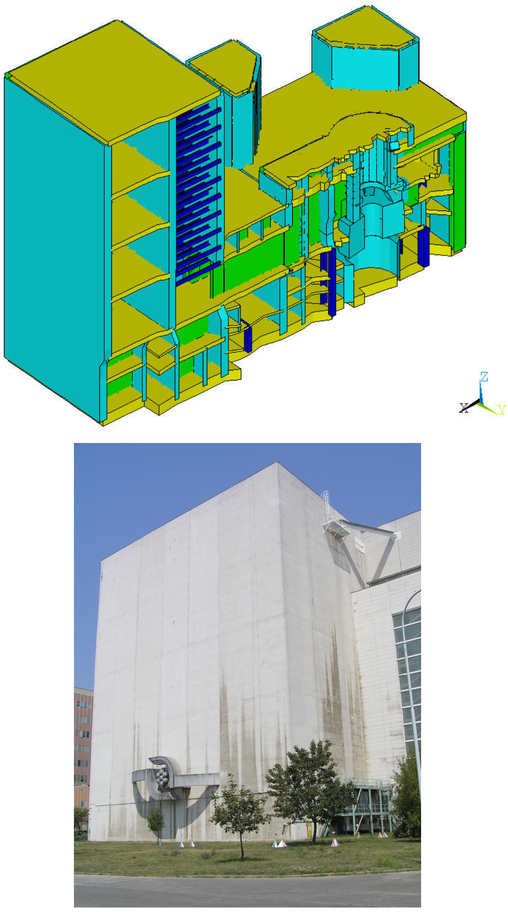

Fig. 1 Calculation model and the view to the NPP building

2. Probabilistic safety assessment

Probabilistic safety assessment (PSA) level 2 [1, 6, 9] is a systematic way to study, from the point of view of safety and with the restrictions of a specific methodology, the behaviour of a system (NPP under accident or quasi-accident conditions) when uncertainty is present and widespread. The starting point of level 2 is the result of a PSA level 1. The results of such study is a huge quantity of the accident sequences that are grouped, according to the different criteria regarding the accident characteristics and the potential containment responses, into a manageable number of plant damage states (PDS). After an appropriate screening of a very low probability sequences, the probabilistic progression of accidents is studied using event trees, commonly known as the accident progression event trees (APET) or the containment event trees (CET), under two possibilities: large event trees (virtually all questions regarding severe accident are included as top events) and he small event trees (only main questions regarding severe accident phenomena are included as top events). The use of these event trees leads to get-ting a huge quantity of end states, that have to be grouped, as in the case of PDS's, to get a more manageable set of release categories, later used to estimate all the variety of the different possible source terms. The appropriate combination of the release categories and the corresponding frequencies allows estimating the risk associated to the NPP.

The uncertainty is really pervasive in a PSA level 2. The first matter of concern is the starting point. A lot of methods and tools do exist to study the influence of uncertainties on the results of severe accidents computer codes in use for PSA level 2. There are a lot of reports on the subject in the scientific literature (NEA 94, NEA 97, and NEA 99) [9]. The item "influence of uncertainties" means, in this paper, the uncertainty analysis or the sensitivity analysis or evaluation of the probability of exceeding a threshold. So we could say that uncertainty arises in three areas of the PSA level 2: 1) Definition of the plant damage states, 2) Simulation of the problem, including event tree construction and models (computer codes) used to simulate the physical-chemical processes involved, and 3) data used to feed models. This is what classically has been considered scenario, model and data uncertainty.

3. Plant damage state definition and quantification

The plant damage states (PDS) form the starting point for the level 2 analysis [9]. Each PDS consists of a collection of core damage sequences, which are expected to behave similarly following the onset of core damage.

The purpose of grouping core damage sequences into PDS is to make the level 2 analysis more manageable and understandable. Given that all sequences in a particular PDS are expected to behave similarly, only one confinement event tree will be needed for each PDS, rather one for each Level 1 core damage sequence.
The process of defining PDS begins with the identification of a set of grouping parameters. These are based on the characteristics of core damage sequences which most influence the post core damage accident progression and hence the releases.
The PDS grouping parameters selected for the Mochovce V2 level 2 PSA are chosen based on the review of other studies [1, 6, 8, 9, and 10]. Parameters, which are judged not to be relevant to the Mochovce V2 case, are eliminated from consideration. In some cases, parameters identified in other studies, which are judged to be relevant, are incorporated into the grouping logic in a slightly different way. Assignment of core damage sequences to plant damage states is performed based on a grouping logic, presented in the form of a decision tree. The PDS grouping parameters are used as headers in the decision tree. Accident sequences are assigned to PDS by following appropriate branches under each header. The appropriate branch to follow is decided based on the characteristics of the particular core damage sequence being considered. The use of a grouping diagram of this type ensures that the process is performed in a systematic, repeatable manner. Another advantage is that the diagram explicitly identifies which combinations of grouping parameter values are possible and which are not.
The PDS grouping logic (decision tree) was develop for both full power and non-full power plant operational states (POSs) [9]. The PDS set includes 69 possible combinations of PDS parameter values. It should be noted that not all of the possible combinations of PDS parameter values need to be considered.
Accident progression was the first parameter considered in the grouping process. Four main source term groups were selected depending on the sequence type: a large LOCA, transients or small LOCA, interfacing LOCA, and open reactor (or fuel pool) sequences. All other parameters were considered within each of these main groups.

3. Scenario for LOCA loads

The accident scenario was defined by VÚJE Trnava [4] in accordance with code MELCOR 1.8.5. The guillotine cutting of the ∅13mm, ∅32mm, ∅71mm and the large break LOCA of the 2x∅500mm (Fig.2) cold leg in the containment were considered. The temperature in the containment increased during the LOCA accident.

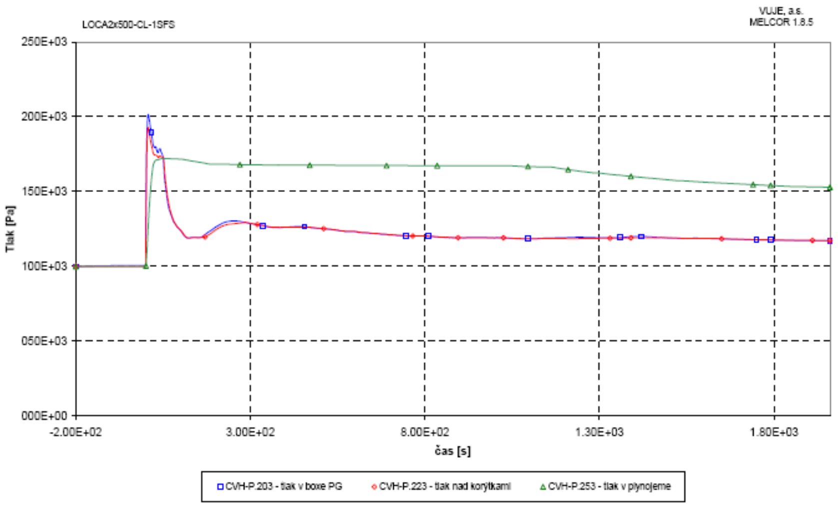

Fig. 2 Absolute pressure in the Box SG for guillotine cutting of pipe 2x∅500mm [5]

The peaks of the temperature are equal to 160°C in the Box SG (Steam generator) by the results of thermodynamic analysis. The effect of these temperature peaks is minimal during the accident and the acting of the overpressure loads. In the case of the harmonic amplitude of the temperature the phase angle for concrete walls is superior to 24 hours. The strength of the concrete after LOCA accident increases about to 10% in consequence of the temperature loads during the accident. The peak of the absolute pressure in the Box SG is equal to 200kPa (the overpressure is equal to 100kPa).

4. Probabilistic analysis of the containment structures

The containment overpressure study is part of the Level 2 PSA [1]. Consequently, the containment's pressure capacity must be expressed in probabilistic terms in such a form that it can be used as input in the overall probabilistic risk assessment. The probability of loss integrity of reinforced concrete structure hence it will be calculated from the probability of no accomplishment condition of reliability *RF*,

$$P_f = P(RF < 0) \tag{1}$$

where the reliability condition is defined by [1] in form

$$RF = R - E \geq 0, \quad \text{various in the form relative} \quad RF = R / E - 1 \geq 0 \tag{2}$$

where R is the resistance of structure, E the effect of action defined by its density. In the case of calculus the resistance of reinforced concrete structure leads off the condition of section integrity. The pressure value could be considered to be the containment ultimate capacity. This pressure capacity value can be determined through structural analysis methods. The conventional analysis is typically based on design configuration and specified design material property values, and as such is deterministic and the computed capacity is a point estimate of the capacity.
Approximation is always made in the analysis and the actual as-built building geometry and the material properties deviate from the idealized design used as basis of the analysis. The uncertainty involved to the calculation has following two important implications:

1. The capacity description must include a quantified description of the uncertainty inherent in the point estimate. The fragility curves must be defined for the Level 2 PSA overpressure studies.

2. The capacity estimates must be determined not only for the weakest link (with lowest point estimate), but also for other weak links along the pressure boundary. Once point estimates and the associated distributions, as well as the level of the correlation between the different failure modes, the aggregate overall description of the containment pressure capacity can be computed using the probabilistic method.

Information from the design calculation and the engineering judgment may identify parts of the containment or doors, hatch covers, etc., as candidates limiting the overall containment pressure capacity. The components/mechanisms with low enough capacities must be analysed to the level of detail considered reasonable for the purpose, eliminating conservatism as possible. The probabilistic analysis of the condition integrity of the containment was realized by simulation of the design check using the LHS method [6, 8].

5. Failure pressure

The failure pressure p_u is determined from the assumption [6], that failure occurs when in the structure the mean resistance counted on the mean material strength R is reached assuming the linear relation between the internal overpressure p and the action effects E corrected by the action effect reducing coefficient

$$p_u = k_r p_{LOCA} \left(R - E_o\right) / E_p \ , \tag{3}$$

where p_u is the failure pressure, p_{LOCA} is the pressure in the case of the LOCA effect (p_{LOCA} =150kPa), k_r is the reduction factor based on assumption of the stress redistribution due to the nonlinear behavior of material, R is the structure resistance (capacity), E_o is the effect of the initial action (dead loads, temperature, performance loads), E_p is the effect of the pressure.

6. Failure function

The reliability of the steel and the concrete structures was checked in accordance of the national standards, Eurocodes and the requirements of US NEA [9] on the ultimate limit state for the median values of the effect of the action and resistance.

The steel structures (hermetic doors and covers) were checked on the effect of the compression/tension forces, the bending moment and the shear forces in the form

$$g(N) = 1 - N_S / N_R \geq 0\,, \quad g(M) = 1 - M_S / M_R \geq 0\,, \quad g(V) = 1 - V_S / V_R \geq 0\,, \qquad (4)$$

where N_S, M_S, V_S are the normal force, the bending moment and the shear force of the effect of the action and N_R, M_R, V_R are the normal force, the bending moment and the shear force of the element resistance defined following

$$N_R = A_v f_{aym}\,, \qquad M_R = W_{pl} f_{aym}\,, \qquad V_R = A_v f_{avm} \qquad (5)$$

The reinforced concrete plane structures were considered on the tension/compression, the bending and the shear resistance. The failure function for the shear resistance is defined following. In the case of the nonlinear analysis of the reinforced concrete structures the failure function can be investigated by the principal deformation values through the section area of the walls. The layered approximation and the smeared crack model of the shell element are proposed. One concrete layer was considered as the orthotropic material for which the direction of a crack is the same as the direction of a principal stress. Function of the concrete failure (loss of integrity) can be defined in dependency to the components of the strain in the crack plane of layer "l" by the failure function in the form

$$g_l(\varepsilon_l) = 1 - \alpha_u \left[\left(\frac{\varepsilon_{1,l}^p}{\xi_1} \right)^2 + \left(\frac{\varepsilon_{2,l}^p}{\xi_2} \right)^2 \right] / \left(\varepsilon_u^p \right)^2 \geq 0 \;;\; \frac{2}{3} \leq \alpha_u \leq 1 \qquad (6)$$

where $\xi = 1$ is the compression, $\xi = \left(\varepsilon^p_{tu} / \varepsilon^p_{cu}\right)$ for the tension. The limit values of the strain are considered following $\varepsilon_{tu} = 0,01$ and $\varepsilon_{cu} = -0,0035$.

The failure function of the whole section will be obtained by the integration of the failure function through to whole section in the form

$$G_u = \frac{1}{h} . \int_0^h g_l\left(\varepsilon_l{}^p ; \varepsilon_{l_u}{}^p ; \xi\right) dz \tag{7}$$

where h is the shell thickness.

7. Variability of the material properties

The statistical characteristic of the material properties must be defined for the probability analysis of the steel and the reinforced structures of the NPP containment. In the case that the site-specific material strength test data are available the median strength and the variability can be obtained from the sample statistics. However, in the absence of the site specific test data in the current study, the median material strengths and the variability were estimated based on the nominal specification values adjusted based on the generic data in the literature and the experience from other containment investigations. The median values and the variability were characterized assuming that all of the material strengths could be characterized by a lognormal distribution.

The following propositions for the steel and the concrete material were considered.

➲**Steel** – the steel structures of the hermetic doors and the covers [6] were made from the steel type 11378.1 (cast 422630.1) and type 11523.1 (cast 422660.1). The reinforcing steel used in the Mochovce is from the type 10216(E) and 10425(V) in dependency on reinforcing steel diameter. The reinforcing bars (rebar) larger than 10 mm in diameter have a nominal yield stress of 410 MPa, while 10 mm bars and smaller have a nominal yield stress of 206 MPa. The nominal strength values are at 95% confidence level in accordance to Eurocode. We proposed an estimate of 8% coefficient of a variation, σ. The following formula relates the median f_{sm} of a lognormal and normal distributed f_s and the 95 percentile value $f_{s.95}$

$$LN: \ f_{sm} = f_{s.95} \exp\left(1,65\sigma\right) = 1,14 f_{s.95}; \quad N: \ f_{sm} = f_{s.95} / \left(1 - 1,645\sigma\right) = 1,15 f_{s.95} \tag{8}$$

➲**Concrete structures -** In the evaluation of the strength of the concrete elements loaded in the compression or the shear, the capacity is dependent on the compressive strength of the concrete, f_c. The containment concrete structures were made from concrete BIV/B330 (equivalent is B25-B30 by EC2) [6] with a nominal compressive strength of 25MPa, were specified for the Mochovce containment structural elements. The concrete compressive strength used for design is typically specified as some value at a specific time from mixing (for example, 28 or 90 days). This value is verified by laboratory testing [6] of a mix samples. The tested strengths must meet specified values allowing a finite number of failures per number of trials.

There are two major reasons for using a median value of the concrete strength above the design strength in evaluating actual structural capacity. First, the contractor attempts to achieve a mix that has an "average" strength above the design strength in order to meet the design specifications. Second, as concrete ages, its strength increases.

As a result, the actual compressive strength of the in-place aged concrete is expected to be greater than the nominal strength. Typical strength of concrete that has aged in excess of five years is about 1,5 times nominal.

The mean value of the concrete compressive cylinder strength f_{cm} (tensile strength f_{ctm}) is defined in dependency on the design value of concrete compressive strength f_{cd} (tensile strength f_{ctd})

$$f_{cm} = \frac{1,3 f_{cd}}{1-1,645.0,133} = 1,66 f_{cd}\ ; \qquad f_{ctm} = \frac{1,4.f_{ctd}}{1-1,645.0,164} = 1,9 f_{ctd} \tag{9}$$

8. Modelling of the uncertainties

The uncertainties exist in the estimated pressure capacities due to the differences between the analytical idealization of the structure and the real conditions. There are the various possible sources of modelling uncertainties. The quality of calculation FEM model – meshing, approximation, boundary conditions – it has not neglected the influence to value of the internal force distributions. The uncertainty of the internal force distribution, the failure criteria, and used the empirical formulae must be investigated. However, in many instances, the evaluation of these uncertainties would require very detailed analysis and/or extensive data which may not be available. As a result, it is necessary to use subjective evaluation and engineering judgment to estimate these uncertainties.

The non-linear FEM analysis taking into account the effect of temperature would be the ideal approach to this problem but that such analyses are very expensive (for data-intensive and time consuming). Consequently the non-linear behaviour and the effect of temperature have to be accounted to by approximations.

It is well known [3, 5] that due to the non-linear and especially the plastic behaviour of the reinforced concrete structure the different codes allow to take into account the redistribution of the internal forces, primarily the bending moments in a different extent depending on the neutral axis depth, the quality of the concrete, the plastic behaviour of the reinforcement. The amount of the bending moments redistributed in the codes is between 15-30%. The results are such a situation, where the capacity of all the cross sections of the maximal moments is fully exhausted.
In the case of the high internal overpressure the containment concrete walls and plates are loaded by the tension forces and the bending moments. The redistribution of the internal normal forces in a box-like reinforced concrete structure is possible, even in case of tension if the capacities of the walls/slabs in one direction are not uniformly exhausted. Of course, the redistribution of the bending moments is possible too. The very high stresses of the range of the mean strengths cause high plastic deformations which are also contribute to the redistribution.
This effect may be considered by conservative approach using reduction factor k_{red}. Summing up the foregoing arguments it was assumed that a k_{red} = 1,2 which is consistent with a redistribution between 15-30 %.

9. Probabilistic analysis of the failure pressure

The general purpose of the probability analysis of the containment integrity was to define the critical places of the structure elements and to estimate the structural collapse. On the basis of previous investigations of VVER 440/213 reactor buildings, carried out in the USA, Slovakia, Czech Republic and Hungary [1, 2, 3, 5, 6, 7, 9, 10] the following critical structures were identified:

- hermetic doors
- reactor dome
- covers of locks (rectangle and circle)
- tube penetrations
- boundaries of the hermetic compartment (reinforced concrete structures and the steel liner)

The probability check of the structural integrity was realized for the critical places, which were defined from the previous deterministic analysis for the LOCA loads. Probabilistic analysis was realized by numerical simulation on the base of the LHS method using the FReET software [8]. The uncertainties of the input simples were taken in the form of the histograms with the proposed statistical characteristics.
In the case of the critical elements of the hermetic zone boundary the probability density of failure pressure $\varphi(p_u)$ is defined in the form

- vertical steel structures HZ – hermetic doors

$$\varphi(p_u) = k_{\text{var}} k_{red} p_{LOCA} \frac{F_{\text{var}} f_{aym}}{E_{\text{var}} \sigma_{am}} R_{\text{var}} \tag{10}$$

- horizontal steel structures on the ceiling of Box SG - covers HUA, HCČ and SG

$$\varphi(p_u) = k_{\text{var}} k_{red} \left(p_{LOCA} - p_g\right) \frac{F_{\text{var}} f_{aym}}{E_{\text{var}} \sigma_{am}} R_{\text{var}} + 0,9 g_{\text{var}} p_g \tag{11}$$

- steel beams under tanks in the bubbler tower

$$\varphi(p_u) = p_{LOCA} \frac{f_{\text{var}} N_R}{E_{\text{var}} N_E} \left(1 - \frac{g_{\text{var}} E_{\text{var}} M_E}{f_{\text{var}} M_R}\right) R_{\text{var}} \tag{12}$$

- reinforced concrete structures of containment

$$\varphi(p_u) = k_{\text{var}} k_{red} \cdot p_{LOCA} \cdot \frac{F_{\text{var}} f_{tm}}{E_{\text{var}} f_{sym}} R_{\text{var}} \tag{13}$$

where the variable parameters k_{var}, p_{var}, g_{var}, f_{var}, E_{var}, R_{var} are defined in the form normalized histograms with the mean values equal to one. These parameters present the probability density of the input action effect p_{LOCA}, p_g, σ_{am}, f_{sym} and the material resistance f_{aym}, f_{tm}, f_{aym} taken with their mean values. The model uncertainties are considered variable values of the action effects E_{var} and the resistance R_{var}.

The probability density of the input values (Table 1) is taken in accordance of the requirements of the literature [6] and the international standards [1] and OECD [9]. The previous analysis and the design check include the various uncertainties; therefore the results of probability analysis of the containment structural integrity are determined as follows:

➲ The initial items of the investigation of the probability containment structural damage were the input values of structural material strength. In the case of the reinforced concrete containment structure the strength of concrete was verified experimentally on 12 bore concrete samples. On the basis of these tests the quality of concrete after 10 years of operation was determined as the concrete of class B30 ("best estimate") with the standard deviation 11, 1%.

➲The basic starting points and the evaluation of the mechanical properties correspond to the assumptions and the advances also used in the other projects [9], the deviations (differences) are in the interval 8-12 % that can be determined by differences in the design of various nuclear power plants with the reactor VVER 440/213. In some cases it might the yield conservative values, other non conservative values.

➲The model uncertainties of the nonlinear stress-strain relations of the reinforced concrete structures in consequence with the inaccuracy of the numerical model were considered at 10-15%. The effect of the concrete and the steel liner joint can be included in this deviation.

➲The inaccuracy in the estimation of the temperature values in the structures was determined at 10 %.
➲The other computational assumptions, which neglect any influences (steel frame of the hinged door, holes) are ordinarily conservative. These effects affect no more than 3-5% error.

Table 1. Variable coefficients of the input parameter uncertainties [6]

Variab. quantity x	Density	Mean μ_x	Variab.coef. σ_x	Note
Action effect				
k_{var}	Normal	1,0	0,100	Variability of force redistribution
g_{var}	Normal	1,0	0,100	Dead load variability
q_{var}	Gumbel	0,6	0,210	Live load variability
t_{var}	Gumbel	0,6	0,210	Temperature effect variability
E_{var}	Normal	1,0	0,100	Model variability
Resistance of reinforced concrete structures				
$f_{c.var}$	Lognormal	1,0	0,111	Variability of concrete strentgh
$R_{o.var}$	Lognormal	1,2	0,150	Variability of bending resistance
$R_{v.var}$	Lognormal	1,0	0,100	Variability of shear resistance
$R_{n.var}$	Lognormal	1,2	0,150	Variability of compression strentgh
$R_{sp.var}$	Lognormal	1,0	0,150	Variability of connection resistance
Resistance of steel structures				
$f_{s.var}$	Lognormal	1,0	0,083	Variability of steel strength
$R_{o.var}$	Lognormal	1,0	0,050	Variability of bending resistance
$R_{v.var}$	Lognormal	1,0	0,100	Variability of shear resistance
$R_{n.var}$	Lognormal	1,2	0,100	Variability of compression strentgh
$R_{sp.var}$	Lognormal	1,15	0,200	Variability of connection resistance

The probability analysis of the concrete structure integrity was considered for the LOCA overpressure loads using the equivalent stiffness of the structure and the mean properties of the materials. The uncertainties of the loads level (longtime temperature and dead loads), the material properties (concrete cracking and crushing, reinforcement, and liner) and other influences following the inaccuracy of the calculated model and the numerical methods were taken in the account in the 10^5 modified simulation LHS. The recapitulation from the probabilistic analysis of the failure pressure is presented in the Table 2.

From the recapitulation of the probabilistic calculation of the failure pressure for the condition of the penetration of steel and reinforced concrete structures is clear that the most critical place are the concrete walls under box of the steam generators. The failure pressure is equal to $p_{u.95}$= 486kPa for 95% probability of penetration.

Table 2. Failure probability of the steel and the reinforced concrete containment structures

Element	Distribution	Failure pressure p_u [kPa]					
		Minimum	Maximum	Mean	Variation	Fractil 5%	Fractil 95%
Steel elements of containment							
Hermetic cover pump	N	657,9	4888,3	2003,1	446,6	1268,4	2737,8
HCP	LN					1330,5	2772,1
Hermetic cover agregat.	N	794,6	6539,5	2438,2	544,6	1542,3	3334,1
HUA	LN					1618,0	3376,0
Hermetic cover	N	416,6	3372,7	1311,0	289,1	835,4	1786,6
HC	LN					875,6	1808,3
Big hermetic door	N	157,6	1459,3	612,3	138,1	385,1	839,5
BHD	LN					404,3	850,1
Herm.reactor shaft door	N	951,5	8807,9	3659,6	833,7	2288,2	5031,0
HRSD	LN					2404,0	5095,2
Hermetic bushing	N	953,4	9883,1	3895,6	878,6	2450,3	5340,9
HB	LN					2572,4	5408,5
Hermetic fit tightly	N	494,9	4581,5	1922,3	433,6	1209,0	2635,6
HFT	LN					1269,3	2669,0
Hermetic valve	N	287,3	890,8	498,3	64,9	391,5	605,1
HV	LN					400,6	610,1
Reinforced concrete structures of containment							
Reactor shaft	N	316,8	5132,4	2276,7	479,4	1488,1	3065,3
RS	LN					1554,7	3102,2
Bubbler tower	N	174,6	1615,2	599,6	135,3	376,9	822,2
BT	LN					395,7	832,6
Box of steamgenerator	N	103,3	955,2	354,6	80,0	222,9	486,3
BSG	LN					234,0	492,4
Steel structures of bubbler tower							
Steel beamof BT	N	300,1	2913,5	978,1	220,7	615,1	1341,1
SBBT	LN					645,7	1358,1

Note : N – normal distribution, LN – lognormal distribution

Conclusion

This paper proposed the methodology of the PSA 2 level analysis of the NPP hermetic structures penetration under the accident events [6]. The uncertainties of the loads level (longtime temperature and dead loads), the material characteristics (concrete cracking and crushing, reinforcement, and liner) and other influences following the inaccuracy of the calculated model and the numerical methods. The critical concrete structures were the walls of the steam generator box. Their failure pressure is equal to $p_{u.95}$=486kPa (95% failure probability).

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