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PROBABILITY NONLINEAR ANALYSIS OF THE FAILURE OF THE NPP HERMETIC STEEL 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 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 model and resistance uncertainties were taken into account in the response surface method (RSM).*

Keywords: Nuclear power plant, Hermetic door, Nonlinearity, Fragility curve, PSA, RSM, ANSYS.

1. Introduction

After the accident of nuclear power plant (NPP) in Fukushimi the IAEA in Vienna adopted a large-scale project "Stress Tests of NPP", which defines new requirements for the verification of the safety and reliability of NPP under extreme effects of the internal and external environments and the technology accidents (ENSREG, 2012). The experience from these activities will be used to develop a methodology in the frame of the project ALLEGRO, which is focused to the experimental research reactor of 4th generation with a fast neutron core. The new IAEA safety documents (IAEA, 2010) initiate the requirements to verify the hermetic structures of NPP loaded by two combinations of the extreme actions.

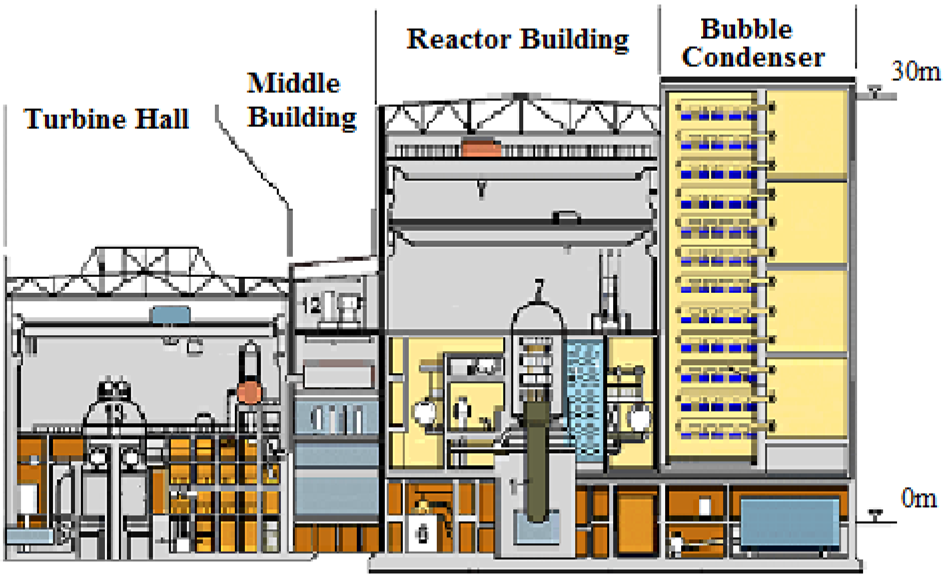

Fig. 1: Section plane of the NPP with reactor VVER440/213.

In the case of the loss-of-coolant accident (LOCA) the steam pressure expand from the reactor hall to the bubble condenser (IAEA, 2010). The reactor and the bubble condenser reinforced structures with steel liner are the critical structures of the NPP hermetic zone (Králik, 2009, 2015). The critical technology steel segments are covers and hermetic doors on the border of containment. The safety and reliability of

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these segments were tested considering the scenario of the hard accidents. The previous analysis was achieved for the overpressure value of 100 kPa due to design basic accident (DBA), which corresponds of the loss of coolant accident due to guillotine cutting of the coolant pipe (Králik, 2009). When the bobble tower operates in the partial or zero performance the overpressure is equal to the 150 - 300 kPa

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

Type	Duration	Overpressure in HZ [kPa]	Internal temperature [^{o}C]
I.	1 hour – 1 day	150	127
II.	2 hours – 7 days	250	150
III.	1 year	-	80 - 120

The SE-ENEL proposes the maximum temperature in the reactor shaft is equal about to 1 800 ^{o}C and in the containment around the reactor shaft is equal about to 350 ^{o}C (Králik, 2015). 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 250 kPa, internal temperature 150 ^{o}C and external temperature -28 ^{o}C.

2. Calculation model of hermetic steel door

The hermetic steel doors type A251 (with dimension 1600 / 900 / 50 mm) are located at safety room in the box of the steam generators. The steel doors fulfils both the sealing and shielding functions. The technology segments of the NPP hermetic zone are made from the steel (S235). The steel door is fitted in the frame cast in concrete and sealed to the frame with double rubber packing of 15 mm in width.

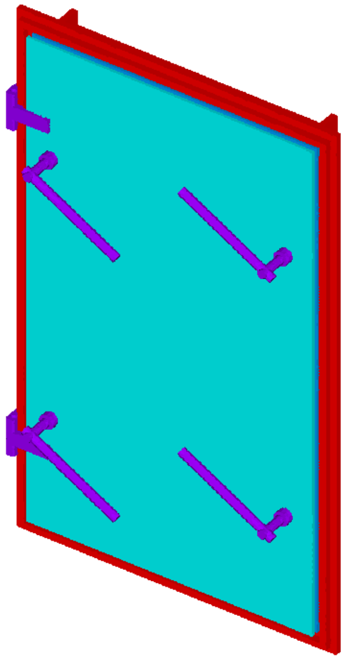

Fig. 2: Hermetic door of the reactor shaft and its FEM model.

The FEM model of the steel door is shown in Fig. 2. Two calculation FEM models of the steel door structures with the steel frame and the mechanical closure were considered. The detailed FEM model has 535 290 SOLID186 and SURFACE154 elements with 140 452 nodes. The simplified FEM model has 86 581 SOLID185 and SURFACE154 elements with 18 393 nodes.

3. Probability and sensitivity nonlinear analysis

Huber-Mises-Hencky model (HMH) of the elastic - plastic steel material properties for MCP steel covering was used. The "Central Composite Design Sampling" (CCD) method of the “Response Surface Method” (RSM) 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 iteration depending on the scope of the plastic deformations in the calculated structures. The uncertainties are coming from the standard requirements and the other publications (Handbook 5, 2005, JCSS, 2011, Krejsa et al., 2015, Sýkora et al., 2013). 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 (see Tab. 2). 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 software ANSYS.

The sensitivity analyses give us the informations about the influences of the variable properties of the input data to the output data (Fig. 3). These analyses are based on the correlations matrixes.

Tab. 2: Variability of input parameters.

Quantity	Charact. value	Variable	Histog. type	Mean μ	Deviat. σ [%]	Minim. value	Maxim. value
			Material				
Strength	F_k	f_{var}	N	1.1	6.6	0.774	1.346
			Action effects				
Dead load	G_k	g_{var}	N	1	5	0.808	1.195
Live load	Q_k	q_{var}	GU	0.643	22.6	0.232	1.358
Pressure LOCA	p_k	p_{var}	N	1	8	0.698	1.333
Temperature	T_k	t_{var}	GU	0.667	14.2	0.402	1.147
			Model uncertainties				
Action	E_k	e_{var}	N	1	5	0.813	1.190
Resistance	R_k	r_{var}	N	1	5	0.812	1.201

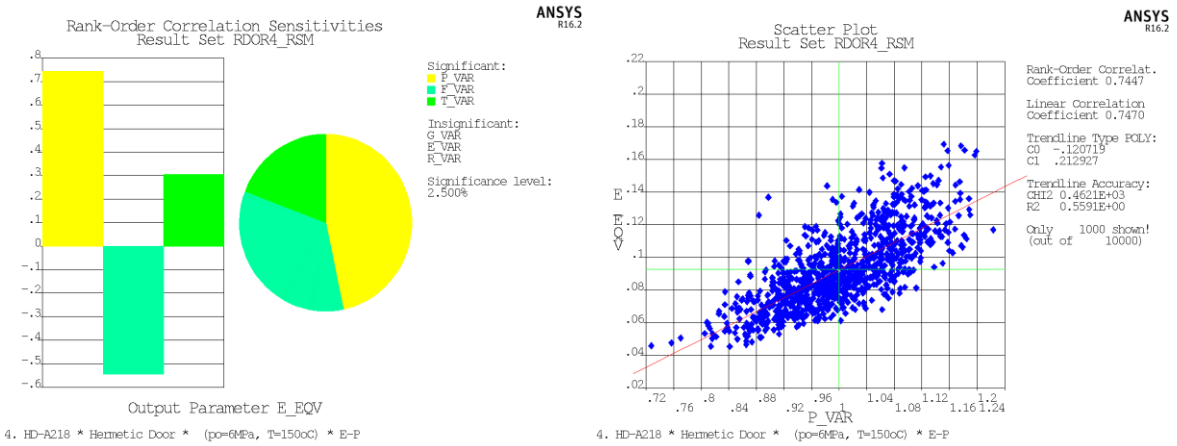

Fig. 3: Sensitivity and trend analysis of the safety function of the steel door of type A251 for the overpressure 6 MPa and temperature 150 °C.

4. Fragility curves of failure pressure

The PSA approach to the evaluation of probabilistic pressure capacity involves limit state analyses (Králik, 2009). The limit states should represent possible failure modes of the confinement functions. The failure of the steel structure is limited with the max. strain values or with the stability of the nonlinear solution (Abraham, 1998). The standard STN EN 1993 1-2 (Handbook 5, 2005) define following characteristic values of the strain for the structural steel – the yield strain $\varepsilon_{ay,\theta} = 0.02$, the ultimate strain $\varepsilon_{au,\theta} = 0.15$, the max. limite strain $\varepsilon_{ae,\theta} = 0.20$. 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 (Fig. 4). 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 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.

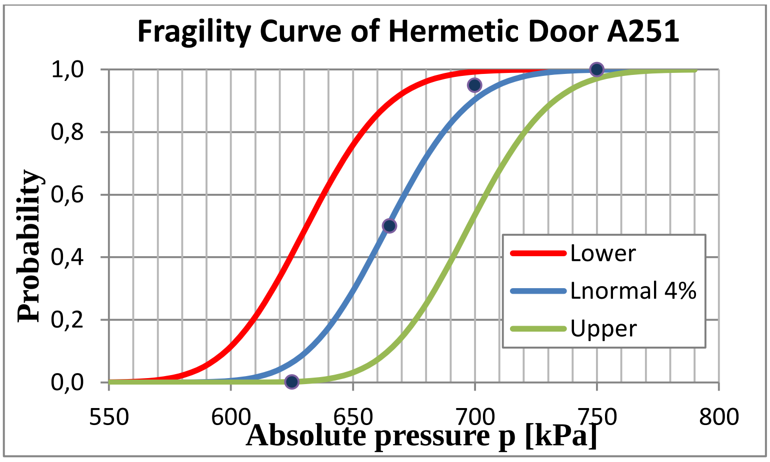

Fig. 4: Fragility curves of hermetic steel door determined for lognormal distribution with 5 % envelope.

5. Conclusions

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 (Králik, 2009, 2015). 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 taken into account in the approximation RSM method for CCD experimental design and 10^6 Monte Carlo simulations (Králik, 2009).

One from the critical technology segments of the containment is the hermetic steel door type A251 with the failure pressure $p_{u.0.05} = 625$ kPa. The mean value of pressure capacity of the steel door type A251 is $p_{u.0.50} = 665$ kPa, the upper bound of 95 % is $p_{u.0.95} = 710$ kPa. These fragility curves (Fig. 4) are the input data for the following risk analysis of the NPP safety.

Acknowledgements

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