

Juraj KRÁLIK¹**OPTIMAL PROTECTION OF REACTOR HALL UNDER NUCLEAR FUEL CONTAINER DROP
USING SIMULATION METHODS****Abstract**

This paper presents of the optimal design of the damping devices cover of reactor hall under impact of nuclear fuel container drop of type TK C30. The finite element idealization of nuclear power plant structure is used in software ANSYS. The steel pipe damper system is proposed for dissipation of the kinetic energy of the container free fall in comparison with the experimental results. The probabilistic and sensitivity analysis of the damping devices was considered on the base of the simulation methods in program AntHill using the Monte Carlo method.

Keywords

Probability, sensitivity, container drop, damping devices, FEM, AntHill, ANSYS.

1 INTRODUCTION

In recent time of permanent demands for increasing of active and passive nuclear power plants safety the question of estimation of the technological equipment resistance after certain operation time is very actual [4, 5, 9, 10, 11, 12, 17 and 18]. The calculation of the containment structure, including personnel access doors, equipment hatches and penetrations and isolation valves shall be based with sufficient margin on design basis events and test conditions. All penetrations through the containment should meet the same design requirement as the containment structure itself Bankash [1], Králik [9, 10, 11 and 12], IAEA [4 and 5]. The new knowledges in the investigation of the nonlinear behaviour of the reinforced concrete and steel structures are utilised [1, 2, 10 and 19]. The nuclear power plant (NPP) structures should be protected against reaction forces stemming from pipe movement or accidental loads such as jet forces, pipe whip and missiles. The load-bearing structure complex analysis for different kind of loads was provided with software ANSYS. The building of a power block was idealized with a discrete model, consists of the solid elements (SOLID 45), shell elements (SHELL43), beam elements (BEAM4), linear actuator elements (LINK11), mass elements (MASS21), solid fluid elements (FLUID80). The overall model consists 20 840 elements and 15 600 nodes.

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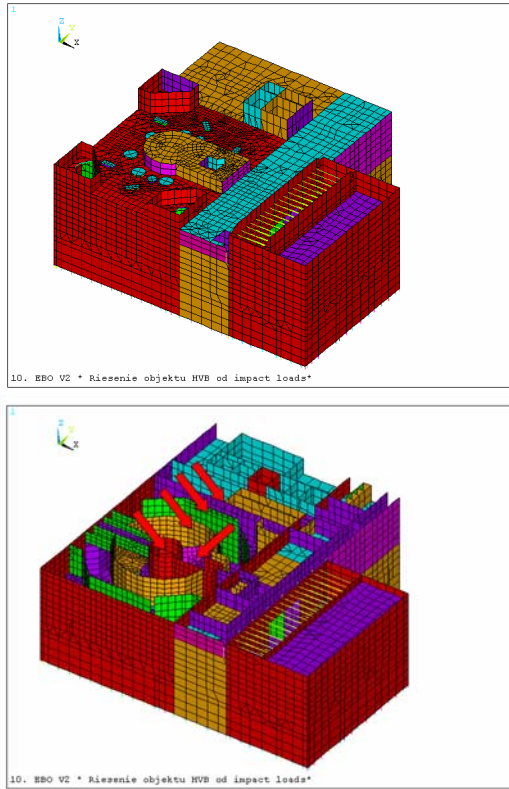


Fig. 1: Calculation model of NPP building with the critical point of container drop

2 CONTAINER DROP

The hall crane transports the nuclear fuel in the steel container TK - C30 under ceiling plate at +18.90 m. The cylinder container has diameter 2285 mm, height 4367 mm and weight 89.5 t. In the case of accident the container can fall to the containment plate. The accident scenario was defined by the technological engineers [10].

We proposed three levels of container fall on the plate from height 200 mm and 3670 mm. The impact loads can be defined from equality of kinetic energy E_k of container weight m_o before impact and potential energy E_p of the plate deformation in moment of maximal impact effect

$$E_k = E_p \quad E_k = \frac{1}{2} m_o \dot{w}_o \quad E_p = \frac{1}{2} k w_{\max} \quad (1)$$

where \dot{w}_o is the velocity of container fall in the moment of the plate-container contact, w_{\max} is maximal amplitude of displacement of the plate, k is stiffness of plate (defined from FEM model of structures). The velocity of the fall \dot{w}_o , long time of the impact t_r and the amplitude of force F_{\max} can be considered as the impact loads in the form of half wave as follows

$$\dot{w}_o = \sqrt{2gh_o} \quad t_r = \pi \sqrt{\frac{m_o}{k}} \quad F_{\max} = k \cdot w_o \cdot \sqrt{\frac{m_o}{k}} \quad (2)$$

where h_o is the height of free fall, m_o is container masses and k is stiffness of plate.

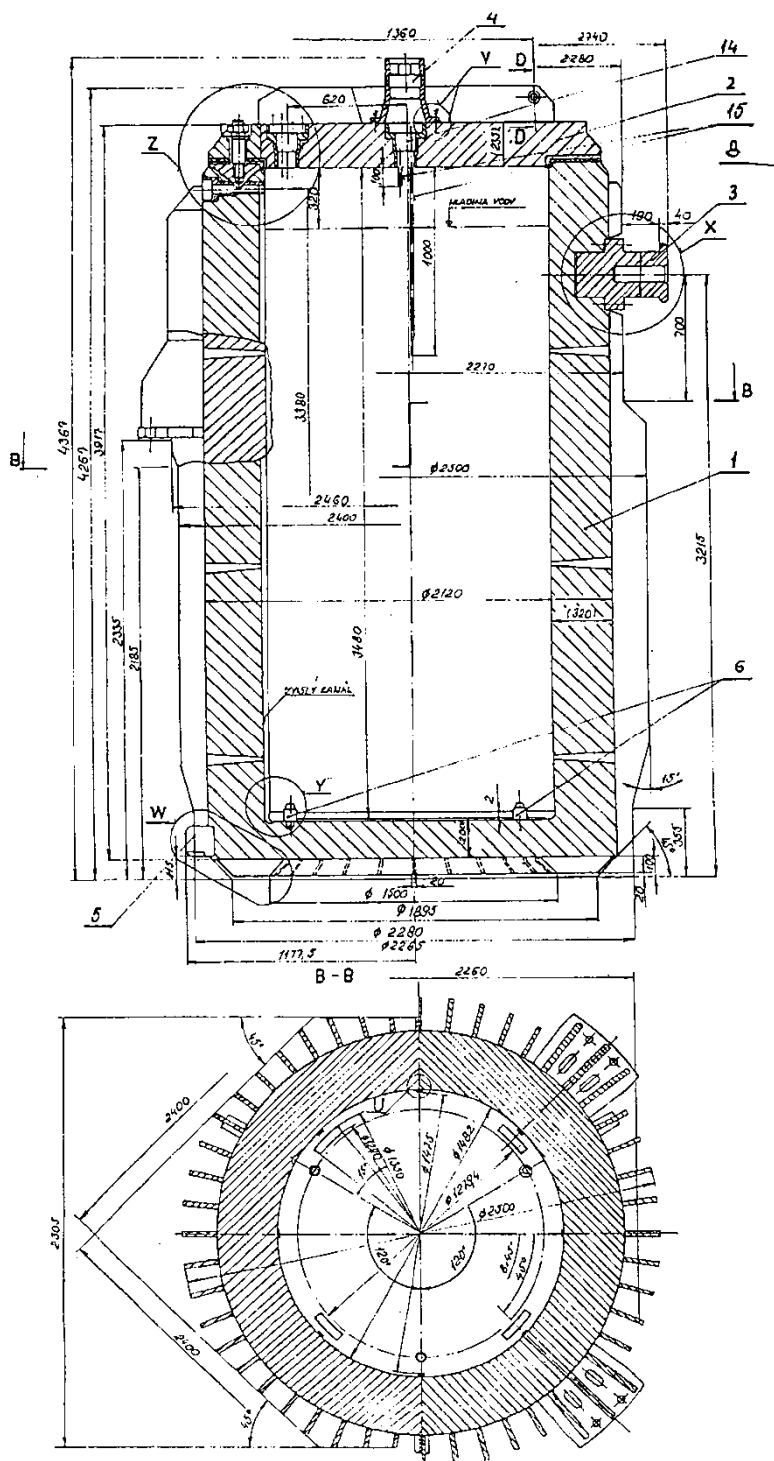


Fig. 2: Scheme of container TK -C30

3 SOLUTION OF IMPACT RESPONSE

In the case of refuelling, during the reactor shutdown, it is manipulated with 85 t heavy containers above the reactor building ceiling. If the suspension is released during this operation, the container can fall down on the ceiling or in the spent fuel storage pond Bankash [1]. Container free fall was defined as an impact load [3 and 9].

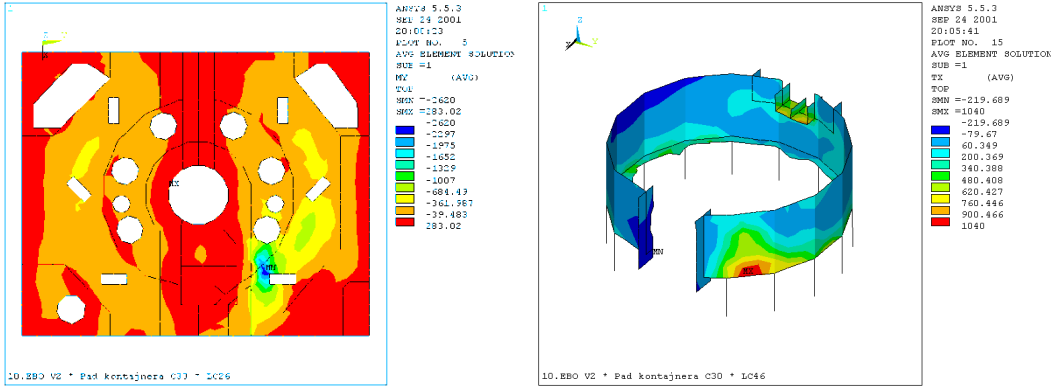


Fig. 3: Envelope of bending moment m_y in the concrete plate at +18.9m and normal forces t_x in the circular wall

The impulse intensity and its duration are expressed from the condition of equality of the kinetic energy of a free falling body and deformation potential energy of the load-bearing structure and the container. The time interval of impulse acting responds to 1/2 of the impulse period. The response forces were calculated on the base of the direct transient method in program ANSYS. The envelope of maximum intensity of the normal forces t_x [kN/bm] and bending moments m_y [kNm/bm] from the impact to the SG box ceiling are presented in Fig. 2. The peak of the bending moment in the concrete plate is near the point of container impact. In the case of the circular wall the peak of the tension forces is on the bottom of wall. Maximum internal forces exceed the bearing capacity of the ceiling plate for about 6% due to the impulse intensity 277.6 MN in the time impulse 0.008 s. In the case of the falling from the height 1.0 m above the water surface in the basin the intensity impulse is equal to 583.07 MN (i.e. 431.35 MN) in the period 0.007 s.

4 DESIGN OF DAMPING DEVICES

Kinetic energy of the free fall container can be dissipated with the plastic energy of damping devices from the pipes in one or two layers both. This type of damping devices was used in Germany [9]. We propose the kinetic energy of the container fall under the bottom of the basin in the form

$$E_k = m_0 gh + m_0 gh_v - \frac{1}{2} \rho A g h_k^2 - \rho A g h_k (h_v - h_k) - \frac{F_v}{2} \frac{h_v - D_s}{h_v} \quad (3)$$

where F_v is the force of the water resistance during the container fall in the basin. The kinetic energy E_k must be absorbed by elastic and plastic deformation of the damping pipe device. The dissipation energy of the plastic deformation of the pipe is expressed following

$$D_p = F_m (f_m - 0.03 D_s) \quad (4)$$

where F_m is the resistance force of the pipe and f_m is the maximum cross pipe plastic deformation.

On the base of experimental results we have

$$F_m = \gamma \sigma_F 2bt^2 \frac{1}{D_s - a} \quad f_m = 0,85 n_L D_s \quad (5)$$

where D_s is the pipe diameter, t is the thickness of pipe wall, a is the length of U profile, b is length of pipe segment, γ is the safety factor, n_L is the number of the pipe layer.

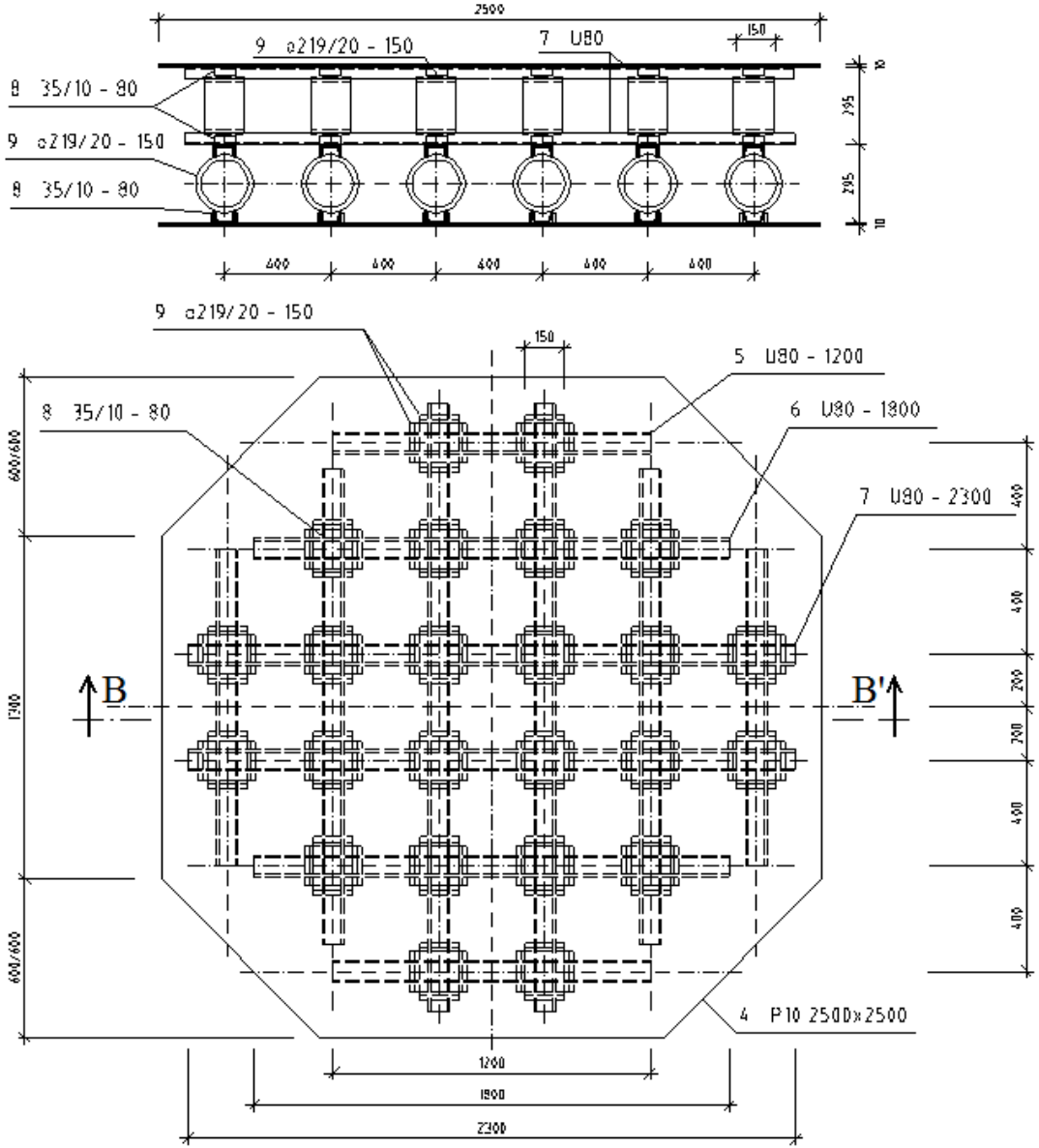


Fig. 4: Configuration of pipe damping device

The potential energy E_p of the elastic and plastic deformation of damping devices is

$$E_p = \frac{1}{2} F_m 0,03 n_L D_s + F_m 0,82 n_L D_s \quad (6)$$

The reliability condition for the design of the damping devices is

$$E_p \geq E_k \quad (7)$$

Two types of the damping devices (Tab.1) were considered. Two of them (type – T1) are designed in one pipe layer, the rest (type – T2) are designed in two pipe layers. The damping devices is proposed from the short pipe elements mutually connected with the steel beams from U-profile in the grid form (Figure 4 and 5).

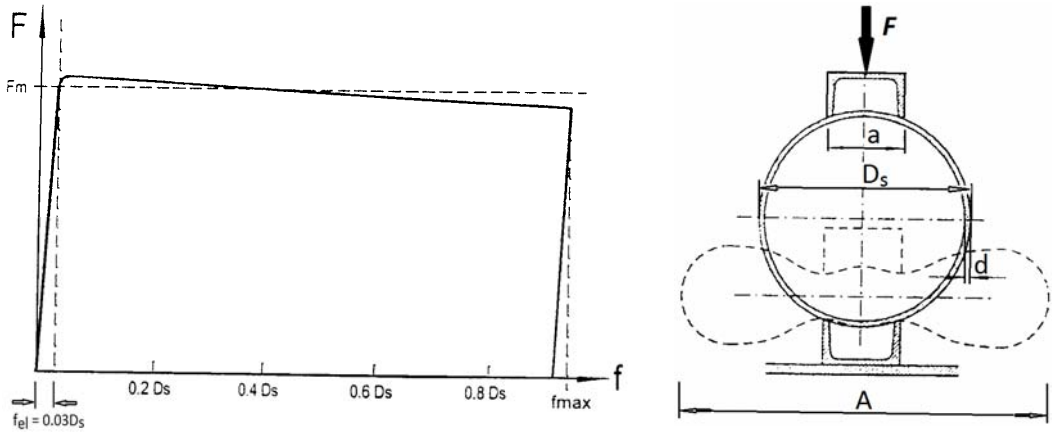


Fig. 5: Experimental test of pipe resistance

Tab. 1: Experimental test of the pipe segment (Bundesanstalt für Materialprüfung)

Specimen No.	Drop in mm	Deformation in mm	Potential Energy ¹⁾ in Joule	Fall velocity ²⁾ in m/s	Deformation Energy in Joule	Load Impulse during 30ms in kN
1	1400	68	10369	5.2	9880	108
2	1600	82	11880	5.6	11300	107
3	1700	72	12516	5.8	11900	110
4	1800	90	13350	5.9	12700	106

¹⁾ This Energie corresponds to the drop plus pipe deformation calculated from targed pipe crack

²⁾ This value corresponds to the velocity of the test frame in the moment of contact with pipe

Tab. 2: Comparison of damping devices effectivity

Type	Diameter of pipe	E_k [kJNm]	E_p [kJNm]	η [%]
Free fall from height 3 670 mm				
T1	1 x 18 x 219/18 – 455 mm	2962.4	2688.0	90.7
T2	2 x 24 x 219/20 – 150 mm	2702.5	2917.4	107.9
Free fall from height 14 010 mm				
T3	1x 24 x 219/22 - 380 mm	4753.2	4471.4	94.1
T4	2x 52 x 219/18 - 150 mm	4644.4	5120.0	110.2

This pipe element was tested by Bundesanstalt für Materialprüfung (see Table 1) for the plastic capacity of the device due to impact load. The safety crosswise deformation of the pipe element was defined on the base of experiment results as $0.85D_s$.

The plastic capacity of the pipe device is defined following

$$F_m = 2\alpha\sigma_f b d^2 / (D_s - a) \quad (8)$$

where α is parameter reliability ($\alpha = 1.1$), σ_F - stress yield ($\sigma_F = 350$ MPa), b - length of pipe, d - thickness of pipe, D_s - diameter of pipe, a - highness.

The maximal plastic deformation of pipe can be use as $0.85D_s$ and the maximal diameter dilatation is $a = 1.5D_s$. Three layer damping devices from pipes 2 x 24 x 219/20 – 150 mm were proposed for dissipate the kinetic energy $E_k = 2702.5$ kNm (free fall from high 3670 mm) with the efficiency $\eta = 107.9\%$. In the case of the basin bottom the effective damping device is design as 2 x 52 x 219/18 – 150 mm which dissipates the kinetic energy $E_k = 5120.0$ kNm (free fall from high 14010 mm) with the efficiency $\eta = 110.2\%$.

5 PROBABILITY AND SENSITIVITY ANALYSIS OF DAMPING DEVICES

The methodology of the probabilistic analysis of the damping devices efficiency results from the requirements [5, 6, 9 and 12] and experiences from their applications [7, 8, 13, 14, 15, 16, 17, 18 and 20]. In this case the direct simulation method MONTE CARLO [15] to solve the reliability of the damping devices was used.

The probabilistic analysis of the accident due the transport way of the container above containment plate results from uncertainty of material and geometry properties, load level, non linear deformation and design condition. The discrete histograms of the AntHill program [15] were used (Table 3). The calculation of the impact response and sensitivity analysis of the damping devices effectivity was considered in the ANSYS program. Three types of the damping devices with various geometry of steel pipes in one and two layers were analyzed (Table 3).

The damping devices (types T1 and T2) were designed for free fall of container on the containment plate. Type T1 is satisfying in the case of 70% effectiveness of the impulse damping, T2 for 80% effectiveness. The damping devices (type T3) were designed for free fall of container on the basin bottom. Type T3 is satisfying in the case of 90% effectiveness of the impulse damping.

Tab. 3: Parameters for the random variable

Variable	Variable coefficient	Bounded histogram	Mean value	Standard deviation	Covariance CoV
F_y - yield stress of steel [MPa]	$F_{y,var}$	LN	392	30.07	0.077
m – container mass [t]	m_{var}	N	85	3.12	3.674
h - fall distance [m]	h_{var}	N	3.67 15.27	0.13 0.57	0.038 0.038
h_n – depth of basis [m]	$h_{n,var}$	N	14.27	0.54	0.037
D – diameter of pipe [mm]	D_{var}	N	219	0.80	3.443
b - length of pipe [mm]	b_{var}	N	46 18	1.72 0.63	3.712 3.513
t – thickness of pipe [mm]	t_{var}	N	28	1.04	37.338
c – width of U beam + plate [mm]	c_{var}	N	77	1.44	18.680
a – height of U beam [mm]	a_{var}	N	80	1.41	17.596
S – area of container [m ²]	S_{var}	N	4.10	0.13	3.120
h_k – height of container [m]	$h_{k,var}$	N	3.917	0.06	0.016

Tab. 4: Parameters for the random variable

Effectivity of damping in %	P_f - Probability of the damping device failure		
	T1	T2	T3
60	0.0	0.0	0.0
70	0.000089	0.0	0.0
80	0.007303	0.000032	0.0
90	0.083356	0.002333	0.000007
100	0.320213	0.030070	0.000818

The sensitivity analysis of the damping devices were realized in the ANSYS program. The results from this analysis show that the effectiveness of the damping devices depends firstly on the material properties of steel – strength and thickness of pipes, secondly on the variability of the container mass and height of free fall.

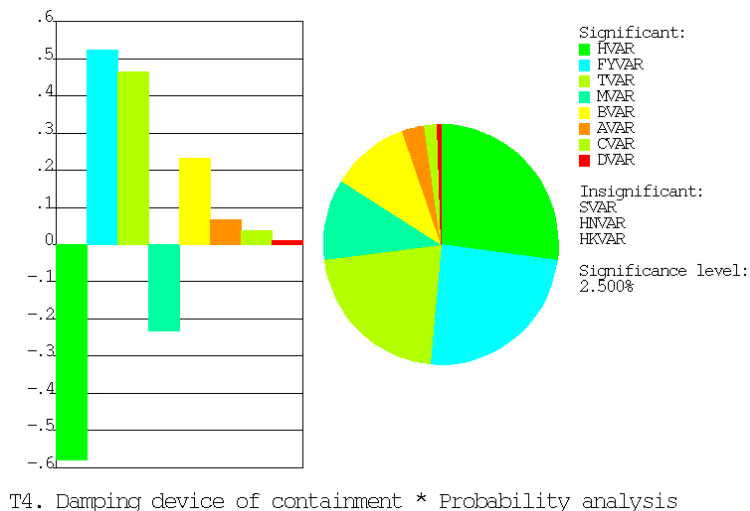
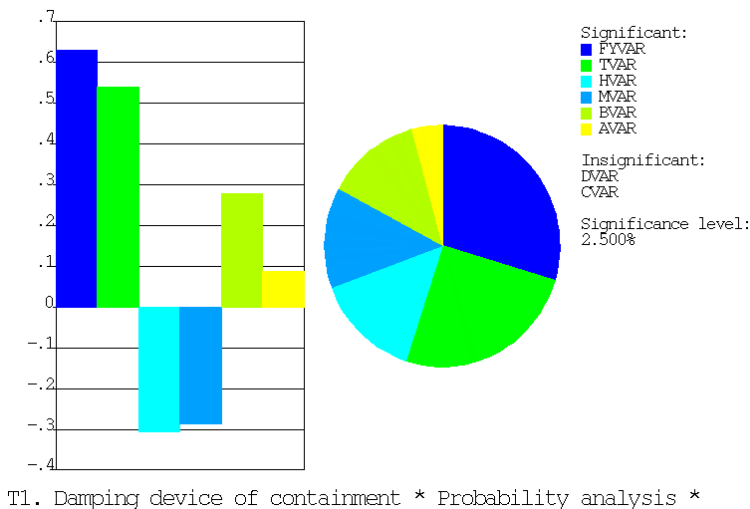


Fig. 6: Sensitivity analysis of the damping device reliability

6 CONCLUSION

This paper deals with the problem of the analysis of the buildings of nuclear power plants in the case of their resistance to the possible accident during the transport of container C30 [4] with the nuclear fuel. The dynamic transient analyses from the container falling during the accident simulation were realized using the system ANSYS. During the reconstruction of the containment structure was designed the damping devices from steel pipes on the base of results of attestats of Bundesanstalt für Materialprüfung. The probability and sensitivity analysis of the effectiveness of the damping devices were realized in the program AntHill and ANSYS. The uncertainties of the loads level (container mass, height of free fall), the geometric and material properties (steel strength, geometric characteristic of pipe segments) and other influences following the inaccuracy of the calculated model and numerical methods were taken in the account in the 10^6 direct MONTE CARLO simulations. In accordance with the probability and sensitivity analysis the reconstruction project of the protection of the NPP building before the crane accident due to transport of the container C30 was proposed.

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