Impact of restrained thermal expansion on RCS structural integrity of Krško NPP

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ABSTRACT

Issues related to the change in mechanical response as a consequence of inappropriate shimming of primary pipe restraints are addressed in the paper. Namely, because of too small clearance between a pipe and a corresponding pipe restraint free thermal expansion of the pipe system during the heat-up could be impeded, thus causing a rise of excessive contact forces in the respective pipe - pipe restraint pair. Locally, this would result in a corresponding development of unexpected and unfavourable strains and stresses both in the pipe and the restraint, while globally, the impediment at one pipe restraint could affect, the piping system being rather stiff, also support forces at distant pipe restraints and interaction forces at piping connections with primary equipment components. So, it is not erroneous to state that in general, with the primary pipe restraints shimming being done inappropriately, a large part of the primary system, and related equipment components as well, could experience a considerable disturbance in the applied loading. In our investigation the Krško NPP system configuration was considered, and to asses the degree of impact, that a restrained thermal expansion due to insufficient shim clearances would have on the reactor coolant system (RCS) structural integrity, a series of numerical simulations was performed. By computer simulation the mechanical response of RCS under various imposed restraint clearances was analysed. The computed results demonstrate a sufficient strength resistance of the primary piping to changes in the investigated kind of loadings, while respective supports are much more susceptible and need careful consideration.

INTRODUCTION

The primary loop supports of the Krško NPP (Westinghouse two-loop PWR type of nuclear steam supply system) were designed to comply two mutually exclusive demands: first, to allow free thermal expansion of the system during the heat-up, and second, to prevent excessive movement of loop components during eventual seismic and accidental events. This is achieved by means of snubbers and bumpers, the latter being shimmed during the hot test to a prescribed, usually very small clearance with respect to the primary equipment components.

During an eventual large loss of coolant accident (LOCA) the bumpers, being in function of steam generator lateral supports, and pipe whip restraints, would experience extreme loads. Accordingly, they were designed mainly to limit the coolant loop displacements after an eventual double-ended guillotine break in the primary piping. Because of the small shimmed clearances, the pipe whip restraints represent actually a potential impediment for loop thermal displacements, causing thus unexpected additional stresses during normal operation.

To check the degree of influence that a restrained thermal expansion would have on the structural integrity, a series of numerical analyses was performed. Therefore, a finite element method based numerical model of the two-loop cooling system, with all for the investigation relevant structural components being considered, was conceived, taking all respective displacement and traction boundary conditions into account. The model was subjected to the loadings associated with the normal operating conditions of the coolant system (dead weight, pressure, temperature). The computational analyses were repeated several times, each by considering a different pipe whip restraint subject to modification of clearance. The range of clearances, within which the values considered in the performed computational analyses were selected, was limited on one hand to the maximal values being equal to the actual built-in clearances, while on the other hand it was set in a way to impose different degrees of obstruction of the primary loop displacements due to thermal expansion. For each simulated restraint case the displacements of the primary piping, as well as the reaction forces in the components supports, were calculated.

Afterwards, with the piping support loads known, a detailed numerical model of hot and crossover leg of the primary piping was used to calculate strains and stresses in the piping for each respective investigated case. Since main concern of the work was focused on the investigation of the system mechanical response under normal operating conditions, the corresponding temperature and pressure field distributions of the coolant were assumed stationary, actually, as established at the end of the heat-up. Therefore, all computational analyses were performed as static, but including a non-linear inelastic material behaviour.

NUMERICAL MODEL

To treat strains and stresses in a pipe wall also for the case of lateral pipe loadings, i.e. pipe restraint forces, in a reliable and objective way, a detailed numerical model is needed. In our investigation this is achieved with the shell-type finite element models covering hot and crossover leg of the primary piping, as shown in Fig. 1. Shape and size of the domains, denoted as A_1, A_2, A_3 and A_4 in Fig. 1, on which lateral forces F_1, F_2, F_3 and F_4 are acting, are determined according to the technical specification [2]. In this figure, though not included in the actual numerical model, the large component primary equipment, consisting of reactor vessel (RV), steam generator (SG) and reactor coolant pump (RCP), is shown only for better imagination of the piping layout.

Primary loading on RCS hot and crossover leg pipes arises from the hydrostatic fluid pressure. Beside the primary loading a very important part is due to secondary loads, such as thermal loads, interaction loads at the pipe junctions with the large component primary equipment, and restraint loads at the pipe supports. With exception of the thermal loads the mechanical analysis of the whole RCS is needed in order to identify the remaining two kinds of secondary loads. Therefore, a corresponding two-loop beam-type finite element model of the RCS was built (Fig. 2) [5,6], containing also beam modelling of the concerned hot and crossover legs (Fig. 1) of the primary piping, which is highlighted by a thick line in Fig. 2. With respect to the shell-type model (Fig. 1), if used also in the modelling of the whole RCS, the beam-type model (Fig. 2) is definitely less accurate. But in view of the avoidance of excessive computational costs and decreased computational time efficiency, due to a tremendous increase in number of degrees of freedom in the shell-type model, the use of such a beam-type model is anyway justified. Having in mind the specific of the investigated problem, with reduced clearances of the pipe restraints shims being considered, of course, a special attention should be paid on proper modelling of the pipe restraints in order to retain also with such a model as much as possible reliable system response. In the same context effects of cross-section ovalization and warping modes of deformation of pipe elbows should be taken into account, with the corresponding equivalent pipe cross section properties, in consequence, being considered in the computation. From the corresponding computational analysis of the RCS mechanical response, in which all the mechanical and thermal loads characterizing normal operating conditions are considered, information relevant for a subsequent, on the shell-type finite element model based, detailed analysis of the considered pipe system can be extracted. This information consists of the computed displacements and rotations, and forces and moments as well, characterizing the mechanical interaction between the pipes and surrounding

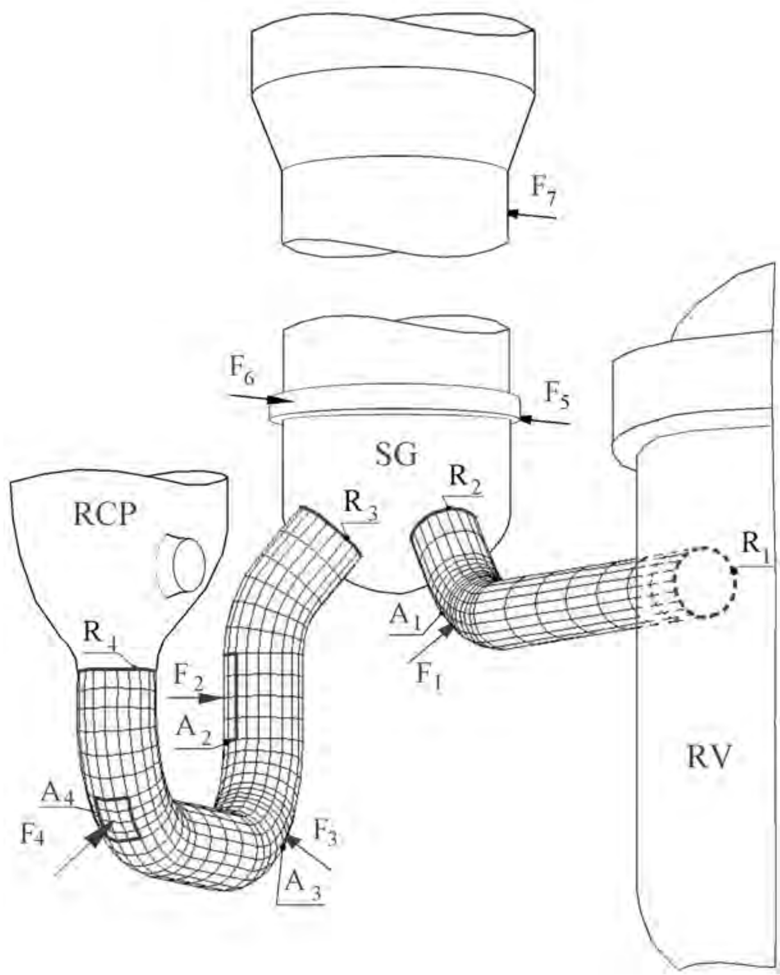

Fig. 1 Hot and crossover leg of the primary piping modelled with shell elements

structural components.

In order to enable a detailed modelling of selected portions of the primary piping, we are actually interested in hot and crossover leg, a substructuring of the RCS is applied. The extracted respective substructures are then modelled with the shell-type finite elements, and subjected to the corresponding boundary conditions, as identified by the beam-type model simulation. The displacements and rotations of points, representing piping terminals at RV, SG and RCP nozzles, are transformed into prescribed displacements and rotations of the respective pipe cross-section planes, in Fig. 1 denoted by R_1, R_2, R_3 and R_4. Besides, pipes are loaded with external forces F_1, F_2, F_3 and F_4, originating from the beam-type model as contact forces due to pipe restraints. Additionally, pipes are loaded uniformly with temperature and internal pressure, according to the normal operating conditions [3].

Thermo-mechanical properties of the primary piping, made of SA 351 CF8A, are obtained from [1,4]. It is worth mentioning here, that for all tubes of the primary piping corresponding mechanical tests were done separately for straight sections and separately for elbows. According to these tests [4, Table 4-1] the yield and ultimate stress for all piping parts is higher than minimal, as specified in [1]. Generally, all straight parts of the primary piping have higher mechanical properties than curved sections. The findings of these mechanical tests are all included in our numerical models.

To evaluate the impact of reduced shim clearance the computation of strains and stresses in hot and crossover leg of the primary piping is performed in accordance with the proposed two-model approach, following a numerical strategy that is summarized in the three following steps:

Step 1 - Imposition of initial clearance at the pipe restraints.

All pipe restraints except one are shimmed to the values, as prescribed by design or by measurement during the hot functional test [2], while clearance at the remaining pipe restraint is numerically set to an arbitrary value, which is lower than by the design or measurement prescribed one. By such a supposition the primary pipe would be, very probably, impeded to expand freely as the coolant temperature increases to the normal operating state, causing thus a

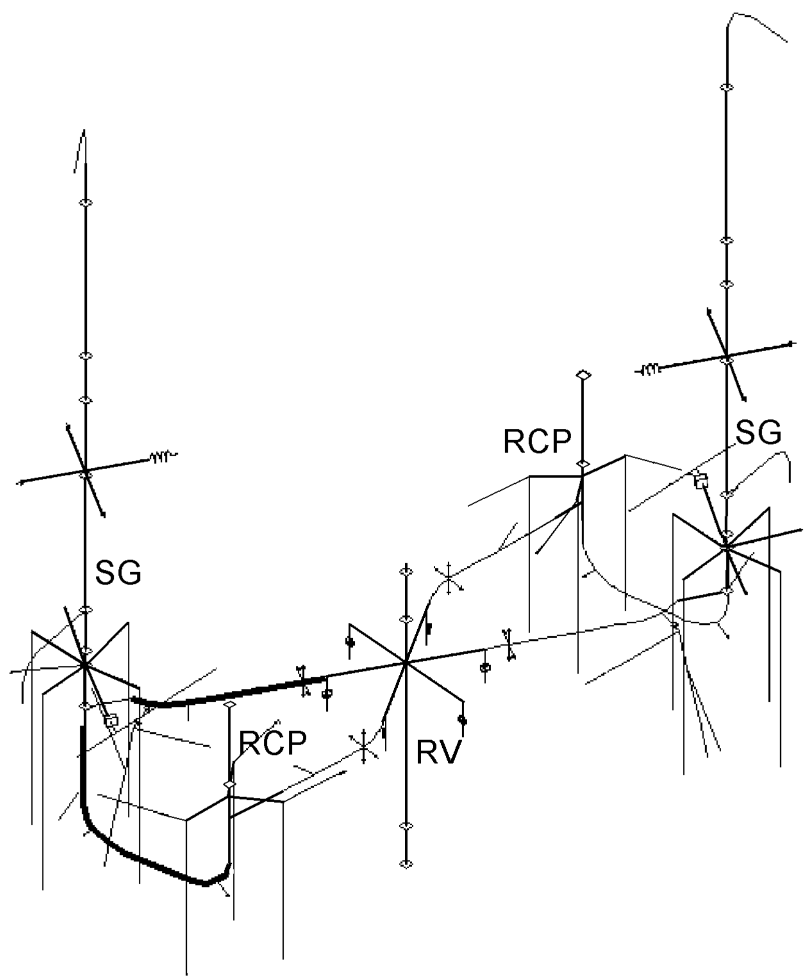

Fig. 2 Two-loop reactor coolant system modelled with beam elements

permanent presence of additional stresses during normal operating of the power plant, that were not considered by the design.

Step 2 - Mechanical analysis of the whole RCS according to the beam-type model.

Since gaps and spring elements are included in the beam-type model of the RCS, a realistic system response to the imposed pipe restraints clearances can be obtained. From the computed analysis results the mechanical response data, indispensable for the subsequent detailed substructure analysis, are extracted. This discrete data set consists of displacements and rotations of RV, SG and RCP nozzles, displacements of the pipe centre-line at pipe restraint locations, displacements of individual pipe restraints (steel construction bearing the restraint is included in the model), and finally, reaction forces at the pipe restraints. Though out of our primary concern, which is definitely the identification of restrained thermal expansion in the normal operating state, the system heat-up simulation results can be effectively used also for inservice inspection and maintenance purposes.

Step 3 - Mechanical analysis of the piping substructure according to the shell-type model.

The shell-type models of the two piping substructures, i.e. hot and crossover leg, respectively, are considered in accordance with the mechanical response of RCS, as obtained by the beam-type model. Consistent solution of the substructure response implies above all imposition of the displacement compatibility at the substructure interface boundary with respect to the previously computed RCS deformation field. Boundary conditions that are applied to the substructure model are therefore given in terms of prescribed displacements and rotations of the pipe end cross-sections, available from one part of the discrete data set, which has been formed at the end of the previous step. In absence of direct modelling of the pipe restraints in the shell-type model the remaining part of the above data set, actually the one including the restrained thermal expansion effects in terms of given contact forces, must be applied to enforce also the corresponding static equivalence. Results of this detailed analysis yield both stress and strain fields, as well as displacement field in the pipes. From the latter the pipe wall indentation can be evaluated.

If a new combination of shim clearances should be analysed then the above procedure is repeated, otherwise the analysis is considered finished. Since in one loop of the Krško NPP there are four pipe restraints, in principle, if impact of the reduced shim clearance at each pipe restraint should be investigated, the described procedure should be repeated at least four times, which has been actually done in our investigation.

RESULTS OF NUMERICAL SIMULATIONS

Since we had no previous knowledge about influence of pipe restraint clearance reduction, the numerical model was built flexible enough to allow any reasonable value of clearance reduction. Being aware, that in real circumstances lessening of clearances with respect to those specified by the design comes out mainly as a result of inaccuracy in the shimming process, the clearance reduction should not be greater than several millimetres, to remain realistic. Eventual gross reduction of clearance is a pure consequence of large errors during heat-up (blocked shims, etc.) and is not covered by this analysis. Accordingly, lessening of 5 mm as a maximal value of clearance reduction is adopted in our numerical investigation.

Simulation of four cases was performed with four restraints, respectively one restraint at hot leg elbow, one restraint at crossover leg vertical run and two restraints at crossover leg 90^{o} elbows, being subject to change in clearance, one per case. In each case clearance reduction of 5 mm on a single pipe restraint is assumed, leaving clearance at all other restraints at their prescribed values. Possible simulation cases, that would take variation of clearance at the pipe whip restraints at RV inlet and outlet nozzles into account, are not considered due to a simple reason. In fact, the prescribed clearance of the considered whip restraints is larger than 5 mm, and as such an eventual reduction of clearance within the assumed range of 5 mm would not affect the mechanical state of RCS. Some results of the performed mechanical analyses are listed in Tables 1 – 6, with numbering of the restraints following labels 1 – 4, as given in Fig. 1.

Impact of the assumed shim clearance settings on the primary piping and SG supports can be seen from Table 1, in which the corresponding results are tabulated. As it was expected, we find out that a reduction of shim clearance on a single restraint can induce huge reaction forces not only at this particular support, but also on other restraint supports. In addition, in case of clearance reduction on crossover leg some of lateral SG restraints become active, too (forces $F_5 – F_7$ in Fig. 1). Effect of the reduced shimming can be seen also through the developed deformation patterns. Actually, as it can be observed from the tabulated displacements in Table 2, the imposition of contact at a restraint by reducing its shimming clearance causes all structural components in contact to displace with respect to the non-contact configuration. The enforced overlapping of the respective pipe - pipe restraint pair, its magnitude being equal to the difference between the imposed change of clearance (5 mm in the considered cases) and prescribed clearance at normal operation (see last column in Table 2), is partly compensated through respective displacements of the pipe's centre-line and pipe restraint's support structure, and partly through pipe wall indentation. While former of the two effects can be attributed to the RCS global deformation, the latter is exclusively a result of purely local pipe wall deformation. With clearance reduction in our investigation being fixed the major factor influencing the mechanical state at particular restraint is certainly the size of overlapping, which is clearly seen from both tables. But, with the overlapping being given, the intensity of the resulting contact force depends first of all on the respective global and local flexibilities. While local flexibility of the pipe wall and global flexibility of the pipe restraint is rather constant, this is not true regarding the flexibility of the piping at the considered restraint. In fact, beside inertia properties of the pipe's cross-section the global flexibility of the piping is first of all determined directly by its layout, and indirectly by stiffness of the large component primary equipment (RV, SG, RCP) to which it is connected. Finally, the flexibility to be used at the considered restraint location must take space dependence of the piping flexibility into account (compare responses at restraints No. 3 and No. 4 in Table 2). It is for all these reasons that results, tabulated in Table 2, need careful background inspection, if general conclusions are to be brought.

Table 1. Primary piping and lateral SG support forces at 5 mm reduced clearance of shims

Clearance reduced at pipe restraint No.	Pipe restraint force [kN]				SG lateral support force [kN]		
	F_1	F_2	F_3	F_4	F_5	F_6	F_7
1	3657	0	0	0	0	0	0
2	0	1438	407	59	665	0	0
3	0	0	3972	3396	0	214	194
4	0	0	3011	5157	721	0	154

Table 2. Primary piping and supports displacements* at 5 mm reduced clearance of shims

Clearance reduced at pipe restraint No.	Pipe centre-line displacement [mm]	Pipe wall indentation [mm]	Pipe restraint displacement [mm]	Prescribed clearance at normal operation [mm]
1	1,868	0,985	1,572	0,8
2	2,164	0,465	0,042	2,4
3	4,453	1,285	0**	0,1
4	3,411	1,667	0**	0,1

* Absolute value of displacement vectors given (not their projected values in the clearance reduction direction), therefore, the sum of all displacement contributions + prescribed clearance can be greater than imposed 5 mm overlapping.

** Concrete support structure not modelled, thus support considered rigid.

In the sequel, values of equivalent Mises stress and equivalent plastic strain at inner and outer surface of the pipe wall for 12 critical points on hot and crossover leg of the primary piping are listed in Table 3. The position of the respective points is shown in Fig. 3. In Table 3, and in following Tables 4 – 6 as well, slash symbol "/" is used to denote that magnitude of the respective physical quantity for a particular point does not differ significantly from that established at normal operating with no reduction of shim clearance. This magnitude is therefore not inscribed in the table. From Table 3 it can be seen that stresses at some points exceed the elastic limit, however, the magnitude of the resulting plastic deformation is small, almost negligible compared to the ultimate plastic strain, which is estimated to the value of 0.25. Considering this evidence a conclusion can be made, saying that even relatively large (5 mm) inadvertent reduction of shim clearance does not result in critical increase of stresses in the primary piping.

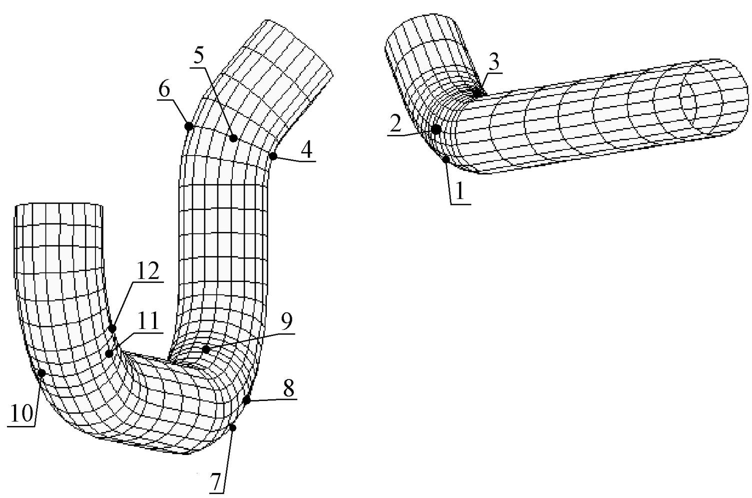

Fig. 3 Position of critical points on hot and crossover leg

Although the change of the stress field in the primary piping, resulting from a reduced shim clearance, is relatively small (but not negligible), the influence of a restrained pipe on other RCS components can be large. Here again, the global flexibility of the piping plays an important role in transferring the effect of the contact force at a pipe restraint to the connecting nozzles. As seen from Tables 4 – 6, in which forces acting on RV, SG and RCP supports are listed, respectively, rather extensive forces can result. To each of the tables three rows, containing the magnitudes of reaction forces at three various operation modes of RCS (normal operation, faulted conditions – without large LOCA, safe shutdown earthquake - SSE) [5], are added in order to obtain better insight of the reduced shim clearance influence on these supports. Indeed, quite a different bearing pattern can be recognized when thermal expansion of the primary piping is impeded. Some compressively loaded support members become loaded even in tension, if the shim clearance is reduced, which is also seen from the tables.

Table 3. Equivalent stress and equivalent plastic strain of primary piping wall at 5 mm reduced clearance of shims

Clearance reduced at pipe restraint No.	Critical point No. (Fig.3)*	Inner pipe wall surface		Outer pipe wall surface	
		σ_{eq} [MPa]	ε_{eq}^{pl} [/]	σ_{eq} [MPa]	ε_{eq}^{pl} [/]
Normal operating conditions (prescribed clearances)	1	87		71	
	2	77		122	
	3	123		110	
	4	125		130	
	5	107		112	
	6	96	0	100	0
	7	80		80	
	8	90		103	
	9	117		112	
	10	86		74	
	11	92		93	
	12	127		119	
	1	159	0,000295	130	
1	2	/	0	153	0
	3	134	0	/	
	4-12	/	0	/	
	1-3, 6-12	/		/	
2	4	154	0	/	0
	5	/		142	
	1-6	/	0	/	0
	7	164	0,000118	154	0,000007
	8	/	0	150	0
3	9	144	0	/	0
	10	164	0,000118	130	0
	11	/	0	140	0
	12	155	0	/	0
	1-6	/	0	/	0
	7	164	0,000080	113	0
	8	/	0	150	0
4	9	160	0	/	0
	10	165	0,000418	166	0,000543
	11	/	0	164	0,000005
	12	148	0	/	0

* Yield stress at Hot Leg temperature (points 1-3): σ_{yield}(SA351, 325°C)=158 MPa,
at Crossover Leg temperature (points 4-12): σ_{yield}(SA351, 287°C)=164 MPa

Table 4. Support forces on RV at 5 mm reduced clearance of pipe restraint shims

		Tangential force [kN] *			
		Hot Leg (R5)	Cold Leg (R4)	(R3)	Hot Leg (R2)
Prescribed clearances	Normal Operation	-24	45	23	-26
	Faulted Conditions [5]	-1161	-2762	-1282	-1299
	SSE [5]	±1508	±1601	±1651	±1534
Clearance reduced at pipe restraint No.	1	/	-507	-497	/
	2	/	-321	-292	/
	3	-180	-477	-302	-248
	4	+179	+435	+194	+86

* Vertical and some tangential support forces remain almost unchanged, thus they are not listed in Table 4

Table 5. SG column forces at 5 mm reduced clearance of pipe restraint shims

		SG Column No. [kN]			
		1	2	3	4
Prescribed clearances	Normal Operation	-868	-1236	-1099	-722
	Faulted Conditions [5]	-903	-1266	-1413	-948
	SSE [5]	-2504,+1063	-3453,+1026	-3137,+933	-3030,+1365
Clearance reduced at pipe restraint No.	1	+367	/	/	+755
	2	/	/	/	-274
	3	+205	+94	/	/
	4	-413	-225	-300	-488

Table 6. RCP support forces at 5 mm reduced clearance of pipe restraint shims

		RCP Column No. [kN]			Tie Rod No. [kN]	
		1	2	3	2	3
Prescribed clearances	Normal Operation	-306	-481	-291	0	0
	Faulted Conditions [5]	-1119,+191	-468,+1747	-889,+797	-200	3543
	SSE [5]	-1194,+416	-835,+406	-546,+1053	-779	827
Clearance reduced at pipe restraint No.	1	/	/	/	/	/
	2	/	/	/	/	/
	3	+461	+792	+713	/	+578
	4	-292	+1223	+1667	-537	/

SUMMARY AND CONCLUSION

Based on numerical simulation of heat-up of the Krško NPP in case of imposed shim clearance reduction the corresponding mechanical response of RCS has been evaluated in view of quantifying the impact of restrained thermal expansion on RCS structural integrity. A 5 mm reduction of shim clearance has been applied at four pipe restraints of one loop of the primary piping separately, while clearances of the restraints on the second primary loop have remained unchanged. Reviewing the analyses results following conclusions can be set:

1 - *Primary piping stress state:* In the worst case, which is the reduction of shim clearance at pipe restraint No. 4 (under the 90^o elbow on crossover leg, RCP side), the maximal equivalent stress exceeds the actual yield stress for 1.2% (σ_{eq}=166 MPa, σ_{yield}(SA351, 287^{o}C)=164 MPa). The size of plastically deformed area of the pipe wall is small, with the amount of equivalent plastic strain being almost negligible (0,00055). Let us mention, that in case of prescribed not reduced restraint clearance, maximal equivalent stress reaches 78% of yield stress, which clearly proves that the evidenced increase of stresses in the pipe is mainly due to indentation of its wall.

2 - *Pipe restraint support forces:* The greatest lateral force acting on the pipe wall appears in the case of clearance reduction on restraint No. 4. The considered case is in fact, among the investigated cases, the most severe one. This is because of the largest overlapping and impossibility of the restraint support deformation (the support lays directly on the concrete wall of the reactor building structure which is assumed rigid), but obviously, which can be find out by comparing the considered deformation pattern with that of restraint No. 3, in Table 3, also because of the

increased piping stiffness at this restraint. The magnitude of 5157 kN of the considered force exceeds distinctly the magnitude of forces owing to upset, emergency and faulted conditions (except large LOCA), acting on the same restraint in case of no shim clearance reduction [5].

3 - *Influence of reduced clearance on the components of RCS:* According to Tables 1, 2, 3, 5 and 6 the greatest influence on RCS response during heat-up is manifested in case of reductions of shim clearance on 90^o elbows pipe restraints on crossover leg, reasons for this being already explained above. Since, due to relatively large ovalization rigidity of the pipe, local effects in the form of pipe wall indentation are not developed largely, the contact loading effects are transferred from the respective restraint through the pipe to the rest of RCS in a rather large extent. In consequence, the RCS support members manifest quite large forces in the supports, actually in the magnitude of SSE support forces. Moreover, the character of the resulted forces can change from compressive to tensile or vice versa. In this context, strength of elements, joining the compressive supports (bolts, nuts, bearings), should be extra checked, while tensile support members should be inspected against buckling.

Upon the investigated RCS mechanical response in the case of considered reduced shim clearances two main conclusions can be made:

1) The equivalent stress in the primary piping scarcely exceeds the yield stress of the piping material at normal operating temperature. Regarding the material ultimate strength, the manifested stress increase is not critical.
2) RCS support members exhibit great changes of respective support forces, therefore a bearing capacity of all supports should be revised.

Although, as it has been demonstrated, the reduced clearance of shims does not actually violate the pressure boundary integrity, the final statement should however state, that any increasing of the loading state due to a reduced clearance is not reasonable. Therefore, eventual shim clearance reduction should be avoided, or at least considered very carefully.

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REFERENCES

[1] ASME Boiler and Pressure Vessel Code, Section II, Edition 1995.

[2] Westinghouse Electric Corporation, *Structural Analysis of Reactor Coolant Loop for the Krsko Nuclear Station,* Volume II.: *Analysis of the Primary Equipment Supports*, WCAP-9316, 1979.

[3] Westinghouse Electric Corporation, *System Standard Design Criteria, Nuclear Steam Supply System Design Transients, 18% SGTP Conditions for Krško*, Rev. 1, 1989.

[4] Westinghouse Electric Europe: *Technical Justification for Eliminating Large Primary Loop Pipe Rupture from the Structural Design Basis of NPP Krško*, SSR-NEK-11.4.1, Rev. 2, 2000.

[5] Laboratory for Numerical Modelling and Simulation, Faculty of Mechanical Engineering, University of Ljubljana: *Stress Analyses of the Primary Cooling Loop in Krško NPP and Evaluation of Applicability of the Leak-Before-Break Concept*, (in Slovene), 1999.

[6] Gilbert Associates, Inc.: Drawing No.: 04 4687 E-304-601, *Reactor Coolant Primary Loop*.