SMIRT 14 – POST CONFERENCE SEMINAR No. 16
“Seismic Evaluation of Existing Nuclear Facilities”
IAEA, Vienna, Austria, August 25-27, 1997

FORMER SOVIET REGULATIONS FOR SEISMIC DESIGN OF NPPs AND COMPARISON WITH CURRENT INTERNATIONAL PRACTICE

Prepared by:

CKTI- VIBROSEISM Co. Ltd., 3/6 Atamanskaya, 193167, St. Petersburg, Russia,
Fax: +7-812-395-1338, E-mail: CVS@CVS.SPB.SU

Victor Kostarev
Alexander Schukin
Alexei Berkovski

FORMER SOVIET REGULATIONS FOR SEISMIC DESIGN OF NPPs AND COMPARISON WITH CURRENT INTERNATIONAL PRACTICE

Victor Kostarev, Alexander Schukin, Alexei Berkovski,
CKTI-VIBROSEISM

SUMMARY

This paper presents a summary of current earthquake design criteria used in former Soviet Regulations for equipment and piping systems of nuclear power plants in light of those used in United States and Japan. The detailed comparative seismic analysis of PWR (WWER) Primary Coolant Loop System (PCLS) according to Former Soviet (Russian) PNAE Code and ASME BPV Code with some comments regarding to Japan Code JEAG - 4601 was undertaken for better understanding of the differences and coincidences of seismic design criteria and requirements. The selection of these three guides for the study has very simple explanation: according to ASME BVPC, JEAG and PNAE the huge majority of existing NPPs has been designed.

INTRODUCTION

The international cooperation in safety and seismic upgrading of existing and new design nuclear power plants as well as increasing coordination role of International Atomic Energy Agency (IAEA) leads to necessity of more clear understanding of the criteria and standards used in different countries in earthquake protection design.

On the other hand since the breakup of the Soviet Union there has been considerable concern from World community and international organizations regarding the safety and, particularly, seismic resistance of Soviet designed reactors and NPPs in whole.

Formerly, there were many attempts to compare different national nuclear safety standards. Among them have to be mentioned one of the first research made by John D. Stevenson in the 1979 and in early 80's, /1, 2./. These and other efforts deals primarily with the texts of the Guides and Standards.

One of the essential obstacles of Codes comparative analysis is a correct translation and right understanding of the specific rules and features of the codes in context of assumed general criteria and principles. That is why, for example, the special expert panel consisting of outstanding individuals was established in borders of the USNRC/BNL program for reviewing of Japan Guide JEAG 4601-1987 translation, /3/.

Meanwhile the most of efforts that have been carried out on this way were limited by comparison of Codes coefficients that are have to be used in different design cases and load combinations. Following such an approach rather hard to get the real picture of Codes peculiarities in application to current design situation and current type/class of safety related structure, system, equipment or piping. It is also rather complicated to compare the real Code coefficients of major equipment capacity ratio and Code relative degree of conservatives due to many factors influenced on definition of seismic response, stresses, material properties and evaluation of the strength analysis results.

That is why the most effective and beneficial way, as it seems, is to undertake the direct compare analysis of the same NPP representative system using the given criteria, material properties, formulas and methodology introduced in national or international Codes and Guides.

The present paper contains two comparative calculations of the PCLS (Loop No. 4) of the former Soviet design NPP WWER-1000 MWt Unit. These analyses are based on the application of two national codes: Russian PNAE and American ASME BPVC with some references to Japan JEAG 4601, /4/. The comparison of seismic analysis and calculation methodologies has been performed only for piping systems classified as category I, according to PNAE, class 1 following the ASME BPVC and class As according the importance classification in JEAG 4601.

Only sustained (pressure and weight) and seismic loads were considered in presented analysis. The seismic excitation was chosen as MRZ (Maximal Design Earthquake) according to PNAE, SSE (Safe Shutdown Earthquake) in terms of ASME BPVC and S_2 (Extreme Design Earthquake) as in JEAG 4601. All these levels of design earthquakes are roughly equivalent.

Two methods now are widely applied for piping seismic analysis: RSMAM (Response Spectrum Modal Analysis Method) and THA (Time History Analysis). The first one is mostly common-used method in engineering practice. Use of this method assumes the linearity of the system. External excitation in this case is defined by means of the floor Response Spectra. The second one THA is based on the direct integration of the equations of system motion and it uses as input excitation a real or synthesized recording of the acceleration as time-depended function. It should be noted that application of RSMAM for seismic analysis gives usually more conservative results versus THA. However, when seismic resistance of piping systems is insufficient and the system can be defined like outlier, there is a necessity to install seismic protection (aseismic) devices to withstand an earthquake. In this case only use of more accurate THA with possibility for accounting all non-linearities and peculiarities of piping supports can give the correct results. Nevertheless, all analyses in this report have been carried out by application of more widespread in design practice RSMAM method.

The main purpose of this article is to show on the basis of comparative dynamic analysis of the PCLS the differences and agreements of the PNAE Code and ASME BPVC in procedure of NPP piping seismic design.

GUIDELINES DOCUMENTATION FOR THE SEISMIC ANALYSIS OF NPP PIPING SYSTEMS

The requirements for seismic resistance of the NPP piping systems are contained in the following Russian normative documents and standards:

- PNAE G-5-006-87 "Standard for Design of Seismically Resistant NPPs", /5/;
- PNAE G-7-002-86 "Standard for Strength Analysis of NPP Equipment and Pipes", /6/.

The design and analysis of NPP distributing systems in USA are performed according to ASME BPVC Section III. The main requirements for these procedures are given in the following subsections:

NB-3600 - Design and analysis for Class 1 pipes. This subsection covers 1 Class pipes working under primary loop pressure, /7/.

NC-3600 - Design and analysis for Class 2 pipes. This Class includes the safety-related systems that do not attached in the 1 Class and are working, for example, in accident cooling of protection systems, steam and feedwater pipes, etc., /8/.

ND-3600 - Design and analysis for Class 3 pipes. For example, a system of technical water should be included in this Class, /9/.

The special requirements for piping supports design and strength analysis are contained in the ASME BPVC Subsection NF-3600 "Design Rules for Piping Supports", /10/.

More detailed recommendations and requirements concerned seismic analysis of safety-related NPP piping systems are given in the following Appendixes:

Appendix N “Dynamic Analysis Methods”, /11/;

Appendix F “Rules for Evaluation of Service Loading with Level D Service Limits”, /12/.

Additionally for the main parts of ASME BPVC there is an actually issuing by NRC the special documents, such as RG and SRP. These documents provide specification of requirements for equipment classification, combination of loads and describe a new analysis methods. Up to now NRC issued 21 RG and 11 SRP regarding piping systems. All items concerned seismic analysis among above-mentioned documents are pointed in the References, /13-22/.
In Japan the rules for seismic design of Class As piping is concentrated in JEAG 4601, /4/.

EQUIPMENT CLASSIFICATION

All NPP equipment and piping systems are divided in PNAE as well as in ASME BPVC on the groups A, B, C and Safety Classes 1, 2, 3. The basis for such classification is the importance for nuclear safety of these systems, /18, 23/. Taking into account these circumstances the current consideration contains the seismic comparative analysis of WWER-1000 PCLS, that is classified as Class 2 of PNAE and as Class 1 of ASME BPVC.

PNAE divides NPP equipment and pipes on the two seismic categories I and II, /6, 7/.

In contrast with PNAE, ASME BPVC contains only one seismic category I. This category includes all components and equipment for which is designated to remain their functionality if an SSE occurs, /13, 17/.

In the JEAG all major equipment is divided on four Classes of Aseismic Importance Classification: As, A, B and C.

The following Table illustrates various classifications of the considered PCLS according to different Codes.

Code	Group	Class	Category
PNAE	B	2	I
ASME	A	1	I

According to JEAG 4601 PCLS belongs to the highest As Class.

PIPING COMPONENTS STRENGTH ANALYSIS

Both Codes: PNAE (for all Classes) as well as ASME BPVC (for Class 1) require performing of strength analysis by checking the primary stresses on the basis of maximum shear stress theory of failure, /6, 7/. These primary stresses are divided to the general membrane stresses, local membrane stresses and bending stresses. The specific side of primary stresses is that they are not self-limited and caused by external loads like internal pressure, inertial and weight loads, seismic inertial loads and so on.

Taking into account that according to ASME BPVC the strength analysis is performed only on the basis of membrane stresses and general bending stresses, the comparative seismic strength analysis in this report has been carried out only for $(\sigma_s)_2$ PNAE stress category.

Table 1. contains the dependencies for the nominal allowable stresses applied for pipe's elements, /6, 24/. The JEAG allowable nominal stresses Sm roughly the same as in ASME.

Table 1 ALLOWABLE NOMINAL STRESSES

Code	Symbol	Allowable Nominal Stresses
PNAE	[σ]	for all steels - min $\left\{ R_m^T / 2.6 ; R_{p0.2}^T / 1.5 \right\}$
ASME	S_m	ferrous steels - min $\left\{ S_T / 3 ; 1.1 S_T^T / 3 ; S_Y^T / 1.5 \right\}$ austenitic steel - min $\left\{ S_T / 3 ; 1.1 S_T^T / 3 ; S_Y / 1.5 ; 0.9 S_Y^T \right\}$ [1)]

1) Choosing of allowable stress according to this expression may result in a permanent strain of as much as 0.1%. When this amount of deformation is not acceptable, the designer should reduce the allowable stress to obtain an acceptable amount of deformation.

The values of defined above stresses for different materials are presented in Table 2.

Table 2 ALLOWABLE NOMINAL STRESSES, MPa

Material	T,°C	[σ]	S_m
St.20	250	130	130
15GS	300	150	150
08H18N10T	300	118	118

It should be noted that the values of allowable stresses, calculated according to ASME BPVC may be independent from service temperature (in the case, when S_m=S_T/3), so all comparative results are valid only for given material and service temperature.

The main difference between ASME BPVC and PNAE is identification in accordance with ASME BPVC four Levels of Service Limits Loading for each component or support. These Service Limits may be designated in the Design Specification and defined as different Levels (Levels A, B, C and D). It should be pointed that seismic loads are considered in strength analysis only for Levels B and D (Appendix A, SRP 3.9.3, /22/).

In the further consideration only the Level D Service Limits will be applied for seismic analysis of PCLS. The NCA-2142.4 gives the following definition of these Service Limits:

Level D Service Limit. Level D Service limits are those sets of limits which must be satisfied for all Level D Service loading identified in the Design Specification for which these Service Limits are designated. These sets of limits permit gross general deformations with some consequent loss of dimensional stability and damage requiring repair, which may require removal of the component from service. Therefore the selection of this limits shall be reviewed by the Owner for compatibility with established system safety criteria (NCA-2141).

The PNAE does not postulate Levels of Service Limits, which permit some damage of equipment and piping for given set of design loading. Anyway, the different combinations of loading sets present in PNAE (NUE, NNUE, AS) as well as ASME BPVC (SL, LOCA, DBPB, MS/FWPB). So, herein only influence of seismic loading (MRZ or SSE) will be considered, /5, 6, 22/. Table 3. contains the comparison of allowable stresses for pipes.

Table 3 ALLOWABLE STRESSES

Code	Level	Class	Category	Loading	S_a
PNAE	-	2	I	NUE+MRZ	1.8[σ]

ASME	D	1	I	SL+SSE	3.0 S_m
JEAG	-	As		SL+S2	3.0 S_m

The comparison of allowable stress values for different materials in accordance with ASME BPVC and PNAE is presented in Table 4.

Table 4 ALLOWABLE STRESSES, MPa

MATERIAL	PNAE	ASME	ASME /PNAE
St. 20	234	390	1.67
15GS	270	450	1.67
08H18N10T	212	354	1.67

Table 4 shows that the level of allowable stresses calculated according to PNAE (Category 1) are essentially lower than corresponding values obtained from ASME BPVC.

Table 5 contains the formulas for stress calculations for both codes, /6, 7/.

Table 5 FORMULAS FOR PIPING STRESS CALCULATIONS

CODE	STRESS CATEGORY	PIPING ELEMENTS	FORMULAS
PNAE	$(\sigma)_2$	Straight pipes and bends	$(\sigma)_2 = \sigma_{equ.}$ $\sigma_{equ.}=\sigma_3-\sigma_1$
		Curve pipes with $\lambda \geq 1.4$	$(\sigma)_2=\dfrac{\Omega}{\Psi}\dfrac{\sqrt{M_x^2+M_y^2+M_z^2}}{W}$
ASME	S_{ss}	Straight pipes and bends	$S_{ss}= B_1\dfrac{PDo}{2t}+B_2\dfrac{Do}{2I}M_i$

Note: Appendix contains the detailed list of formulas used for stress calculations.
The formulas here and further are given for information and Codes comparative analysis only.

For further consideration it is useful to define the expressions for limit resulting moments M_i. Such formulas one can obtain from Table 5. For example, M_i for bend elements may be presented as:

$$\mathrm{Mi(PNAE)} = k_1 \cdot [\sigma] \cdot W \cdot \frac{\Psi}{\Omega},$$

$$\mathrm{Mi}(ASME) = \frac{2 \cdot I}{B_2 \cdot D_o} \cdot \left(k_2 \cdot S_m - B_1 \cdot \frac{P \cdot D_o}{2 \cdot t} \right),$$

where k1 and k2 -- coefficients that corresponded to the level of allowable stress.

The numerical comparison of the limit allowable resulting moment M_i which met the strength requirements for both codes have been carried out for PCLS. The main characteristics and parameters of PCLS are given below in Tables 6 and 7.

Figure 1 shows the comparison between values of limit allowable resulting moments calculated for straight pipes and bends with assumption that values of allowable stresses for both codes are equal

(k_1=k_2=1.8). One can recognize from these plots that level of resulting moments for both codes is practically identical.

The other result from this stage of analysis is that for sharp-bend pipe elements (short radius elbow) the value of resulting moment calculated in accordance with PNAE is about 20-30% higher than corresponding value for ASME BPVC. It can be explained by differences in formulas used for stress calculations for these piping elements.

Thus, it can be concluded that formulas for stress calculation according to PNAE and ASME BPVC give practically the same result in the range of service pressures in spite of their slight difference detailed in Appendix.

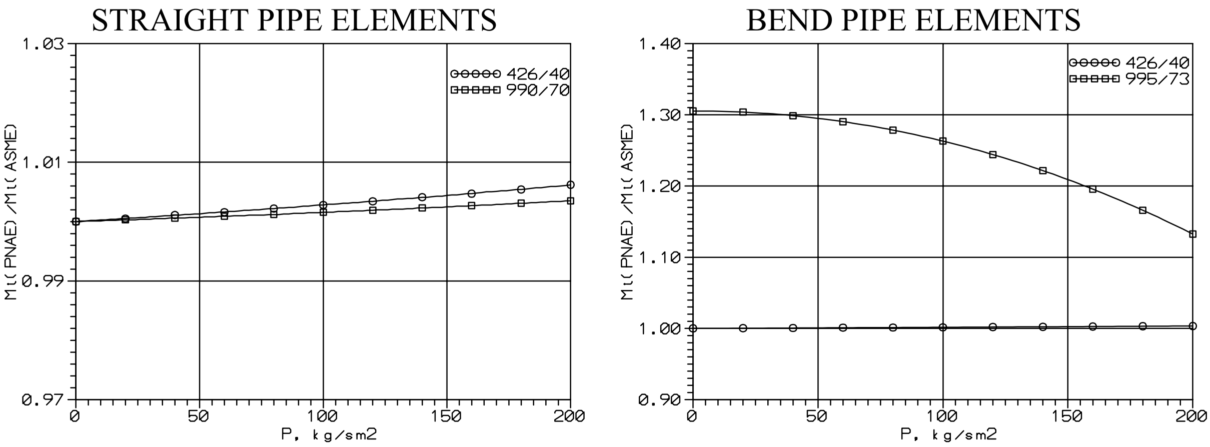


Figure 1 Comparison of resulting moment values, when allowable stresses are equal

However, the ratio between resulting moment values becomes less than 1 when the differences between allowable stresses are taken into account (k_1=1.8, k_2=3), Figure 2. For example, when the pressure value P is equal to 0 MPa the ratio between resulting moments is defined by allowable stresses ratio (340/540=0.63). For P=18 MPa the minimum level of resulting moments ratio is equal to 0.58.

The difference between PNAE and ASME BPVC allowable stresses level results about 70% increasing of allowable moment Mi (ASME) in comparison with Mi (PNAE). It means that piping systems analyzed according to ASME BPVC has less conservative capacity and may withstand to 70 % higher design earthquake level.

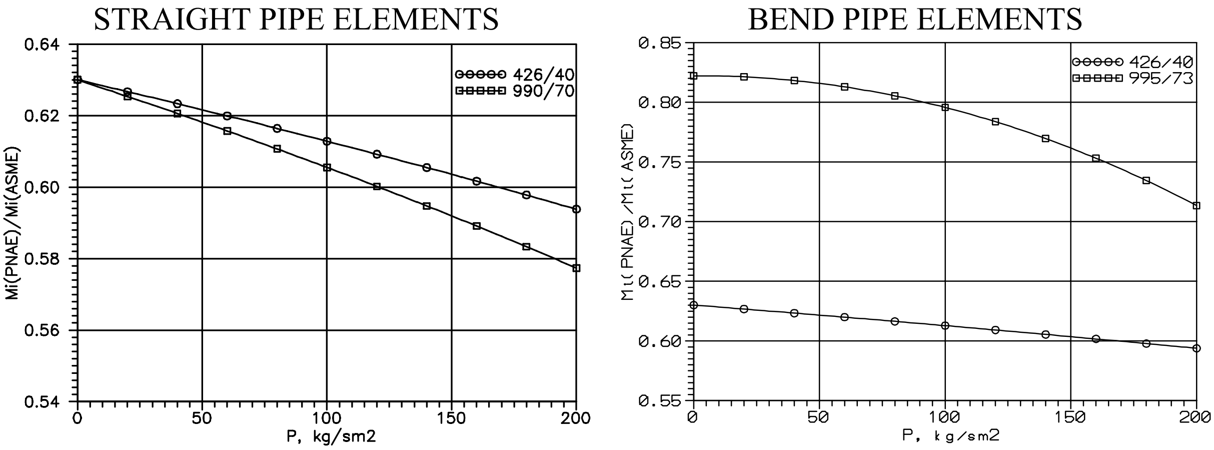


Figure 2 Comparison of resulting moment values, when allowable stresses are different.

DEFINITION OF THE SEISMIC LOADING

The ASME BPVC has a several subsections especially oriented for seismic analysis and design. Among them one of the most important is the Appendix N “Dynamic Analysis Methods”, which contains the article “Seismic analysis”. In this article there are the following items:

N-1210 - “Earthquake description“. This article contains the detailed description and recommendations about applied input seismic excitation in terms of the Response Spectrum and Time History as well.

N-1220 - “Methods of dynamic analysis“. This chapter gives a full range of dynamic modeling and analysis technique description such like THA and Response Spectrum Method.

N-1230 - "Damping”. The recommended damping values for different types of constructions are presented in this article. Also the various methods of incorporating the damping in structural dynamics are given.

It should be noted that the main influence on dynamic response of system, when all other conditions are identical (i.e. seismic excitation, analysis method) has the level of system damping accepted for analysis.

The PNAE postulates for piping systems and equipment damping ratio equal to 2 %. This value is not depended from piping diameter/design nor from the level of seismic excitation. /1, 2/

On the contrary with PNAE the ASME BPVC provides the different values of damping which are depended from the seismic excitation level and pipe output diameter. In the Japan JEAG 4601 the damping values depends on type of piping, number of supports and insulation parameter and vary from 0,5 to 2,5%.

Table 8 demonstrates this influence and contains the damping ratio values recommended for seismic analysis, /11, 25/.

Application of the Case N-411-1 may significantly reduce the seismic response up to 30-35 % in comparison with values originally used in ASME BPVC /11/.

Table 8 DAMPING VALUES FOR PIPES ACCORDING TO ASME BPVC.

Pipe	Level B	Level D	Case N-411-1		
	OBE	SSE	0 - 10 Hz	10 - 20 Hz	> 20 Hz
D > 305mm	0.02	0.03	0.05	0.05 - 0.02	0.02
D < 305mm	0.01	0.02	0.05	0.05 - 0.02	0.02

Note: The Case N-411-1 is recommended for seismic analysis when RSMAM is used.

COMPARATIVE SEISMIC ANALYSIS OF THE WWER-1000 UNIT PRIMARY COOLANT LOOP SYSTEM

The main goal of the comparative dynamic analysis of the PCLS according to ASME BPVC and PNAE is to identify and compare the allowable level of the design seismic excitation, when all elements of piping system meet the requirements of corresponding Code.

<u>Brief Description of PCLS</u>

These main coolant pipelines connect the Reactor Pressure Vessel (RPV) with four horizontal Steam Generators (SG) and form four circulation loops. Basically, all these loops are identical in arrangement and length. Each of loop consist of the hot and the cold legs.

Arrangement of loops differs from each other only in the connected auxiliary pipelines.

To provide coolant circulation between SGs and RPV, the cold leg of each loop is equipped with the Main Cooling Pump (MCP).

Circulation loop equipment (MCP and SG) are supported by the rolling-contact (spherical) bearings permitting free movements in the horizontal plane and taking up the equipment weight.

Due to methodological character of this approach the PCLS without any seismic upgrading devices has been considered.

The main properties of PCLS pipelines are presented in Table 9.

Table 9 PIPING ELEMENTS OF THE PCLS

Pipeline	Element	Do, mm	s, mm	c, mm	R, mm	Q ,N/mm
PCLS	Straight pipe	990	70	3.5	-	21.82
	Bend	995	73	3.65	1340	22.91
PCLS-Pressurizer	Straight pipe	426	40	2	-	5.05
	Bend	426	40	2	1700	5.05

The design parameters of internal medium: Design Pressure P = 18 MPa; Design Temperature: T = 350°C. The pipes are manufactured from 10GN2MFA steel. The mechanical properties of this steel are given in Table 10, /5/.

Table 10 MECHANICAL PROPERTIES AND ALLOWABLE STRESSES FOR 10GN2MFA STEEL, MPA

Material	T,°C	$R_{p0.2}$	R_m	E	[σ]	1.8[σ]	S^*_m	$3.S_m$
10GN2MFA	20	343	540	2.14e5	208	375	180	540
	350	294	491	1.94e5	189	340	180	540

* - $S_m = S_t/3$

PCLS Dynamic Analysis Model.

The dynamic calculation model of the Loop N 4 consists from the hot and cold pipelines of PCLS, SG, MCP and pipeline between hot leg and Pressurizer.

The finite-element approximation of the pipelines and the attached equipment components has been used to create the calculation model of this piping system. The maximum length of pipe elements is defined by the requirements of an accurate modeling of dynamic behavior of the system. All pipes have been modeled by the straight (run) and also by means of the curved (bend) pipe finite elements. The SG has been modeled by means of the straight pipe element with output diameter 4000 mm, wall thickness 110 mm and corresponded lumped masses located in the center of gravity. It should be noted that for modeling of MCP has been used the equivalent beam analytical model /22/. Boundary conditions for piping systems (piping supports and anchorage) are modeled by the boundary and spring elements.

Figure 3 shows the dynamic calculation model of the Loop N 4 of PCLS.

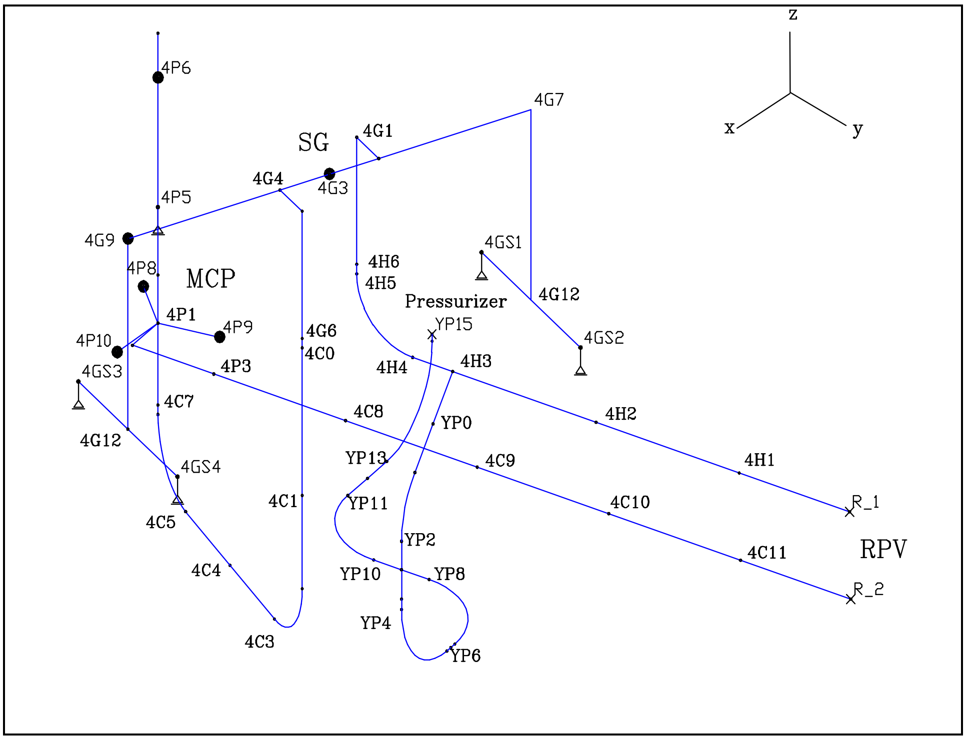
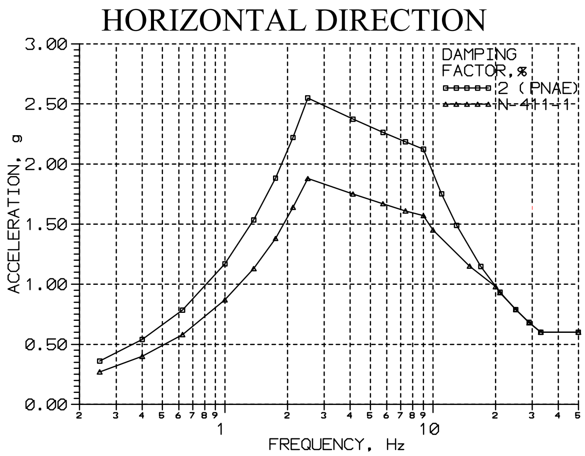


Figure 3 Dynamic Analysis Model of the WWER-1000 PCLS

Input Seismic Excitation

The input seismic excitation for seismic analysis of PCLS has been chosen in terms of Response Spectra given in ASME BPVC Appendix N, N-1211. The considered Spectra have been modified according to damping values for applicable Codes (Figure 4). The plot with 2 % damping corresponds to PNAE case. For ASME BPVC the Case N-411-1 has been used.



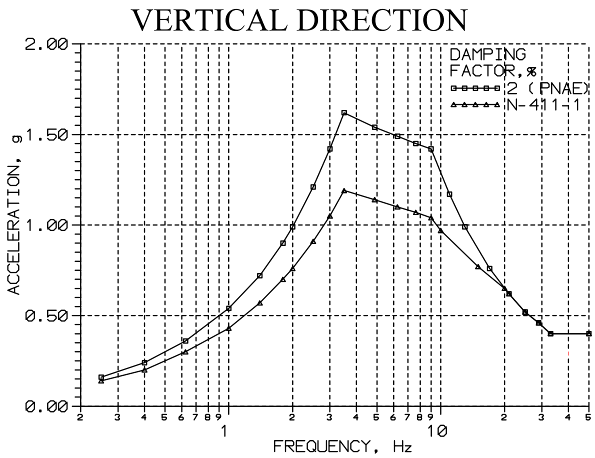


Figure 4 Design Response Spectra

The ratio between vertical and horizontal components of seismic excitation according to ASME BPVC is equal to 2/3, /11,14/. The PNAE does not specified the ratio between seismic vertical and horizontal components. However, PNAE contains item which defined this ratio for building structures as 0.5, /5/.

According to ASME BPVC the following scaling coefficients of Response Spectra were applied for comparative analysis: the horizontal direction -- 0.6, the vertical direction -- 0.4. Thus, for considered Response Spectra the ZPA values for the PCLS floor level were accepted as $ZPA_h = 0.6g$ (the horizontal direction) and $ZPA_v = 0.4g$ (the vertical direction).

ASME BPVC Seismic Analysis

The seismic calculations based on the ASME BPVC NB-3600 requirements have been performed using the “dPIPE” computer program developed by CKTI-VIBROSEISM /27/.

The internal seismic loads for pipeline and equipment of PCLS were calculated with use of RSMAM, when the following assumption have been made, /11, 16, 20/:

- SRSS rule for summation of mode shapes and spatial components of response,
- cut-off-frequency at 33 Hz,
- missing mass effect.

The PCLS pipeline stress values have been obtained from Eq. 9 NB-3650, /7/.

The following output results have been obtained from analysis that performed according to ASME BPVC:

- natural frequencies and modal properties;
- nodal dynamic displacements and accelerations;
- stress values for the straight pipe, bend and tee elements;
- dynamic loads in piping and equipment supports and nozzles;
- resulting static and dynamic internal element loads.

Figure 5 shows the stress values of weakest elements of the PCLS Loop N 4. The strength of these elements is critical for seismic capacity of PCLS.

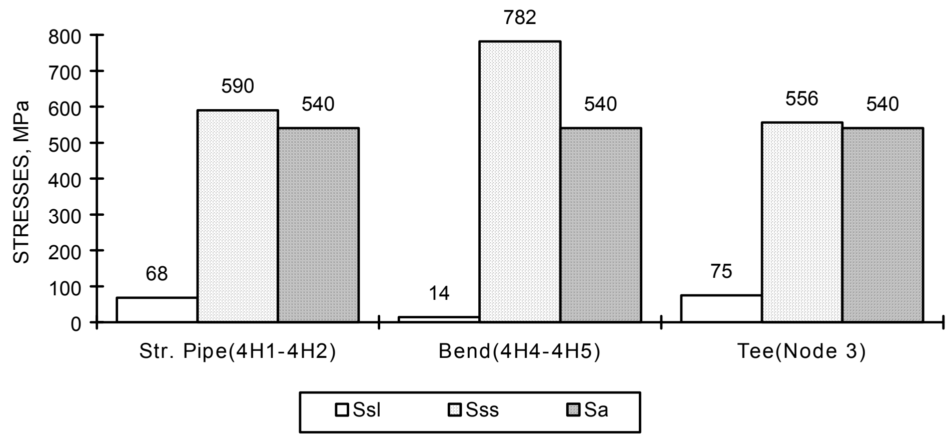


Figure 5 Stress values for selected high loaded pipe elements of PCLS (ASME BPVC)
(S_a - allowable stress, S_{sl} - operation loading stress, S_{ss} - resultant seismic + operation loading stress)

PNAE Seismic Analysis

The seismic calculations according to PNAE G-7-002-86 requirements also have been performed using the same "dPIPE" computer program.

The methodology used for determination of PCLS seismic response is based on the ASME BPVC recommendations (see previous chapter).

The dynamic and static stresses of the PCLS pipe elements have been calculated in accordance with PNAE, Appendix 5, chapter 2 requirements, /5/.

Figure 6. shows the weakest elements stress values for the PCLS Loop N 4. The strength of these elements is critical for seismic capacity of PCLS. It should be noted that for both Code cases these elements are the same. However, the level of stress values, obtained according to PNAE is much higher than corresponding values from ASME BPVC. The calculated dynamic stresses level essentially exceeds the level of allowable stresses.

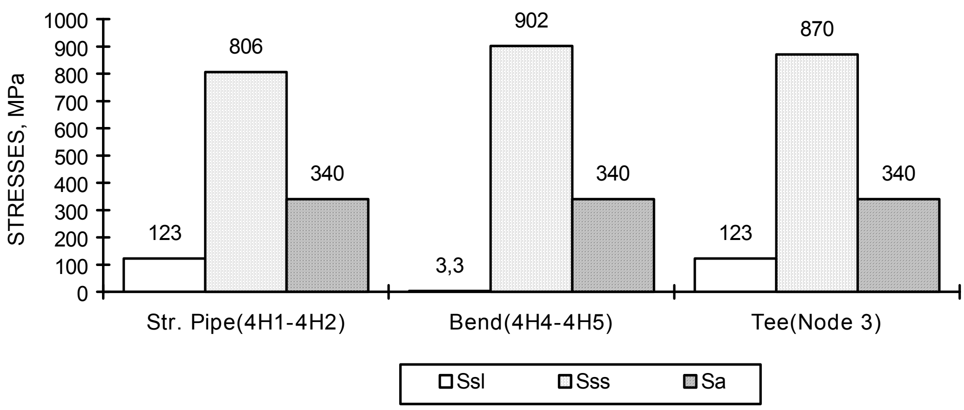


Figure 6 Stress values for selected high loaded pipe elements of PCLS (PNAE)

Comparison of Analysis Results

The following parameters were chosen for comparative seismic analysis:

- dynamic displacements;
- dynamic loads for supports and nozzles;
- stress level in the weakest elements;
- values of seismic margin capacity.

The response of pipeline is strongly depended on acceleration level taken from the input Response Spectra. At the same time Response Spectra acceleration depend on damping values accepted for the analysis. Thus, for identical seismic excitation the response of piping system may be quite different when different damping values are implemented. For example, the ratio between maximal dynamic displacements (node 4p2, X-direction) calculated according to PNAE and ASME BPVC respectively is equal to:

$$Dmax(2\%)/Dmax(5\%) = 431/320 = 1.35.$$

It should be noted that this ratio for given system and seismic excitation corresponds to the ratio between spectral accelerations at frequency 2.5 Hz from PNAE and ASME curves:

$$A_{2.5}(2\%)/A_{2.5}(5\%) = 4.25/3.13 = 1.35.$$

Table 11 contains the comparative data for support and nozzles seismic loads.

Table 11 DYNAMIC LOADS FOR SUPPORTS AND ATTACHED EQUIPMENT

Element of PCLS	Damping	Fz, kN	Mx, N•m	My, N•m	Mz, N•m
Hot Leg nozzle	0.02	8070	4220	43400	2770
	Case N-411-1	5950	3120	32100	2040
Cold Leg nozzle	0.02	1970	2370	31400	821
	Case N-411-1	1480	1800	23300	609
Pressurizer nozzle	0.02	106	337	816	257
	Case N-411-1	79.3	250	639	191
MCP support	0.02	1170	4030	8780	-
	Case N-411-1	1090	2970	6470	-
SG support (4GS1)	0.02	4110	-	-	-
	Case N-411-1	3040	-	-	-
SG support (4GS2)	0.02	4310	-	-	-
	Case N-411-1	3190	-	-	-
SG support (4GS3)	0.02	3940	-	-	-
	Case N-411-1	2920	-	-	-
SG support (4GS4)	0.02	3740	-	-	-
	Case N-411-1	2770	-	-	-

The ratio between dynamic load values for supports and nozzles depends only from intensity of the given Response Spectra and as was mentioned above is equal to 1.35.

Figure 7 shows the comparison of stress values for weakest PCLS elements.

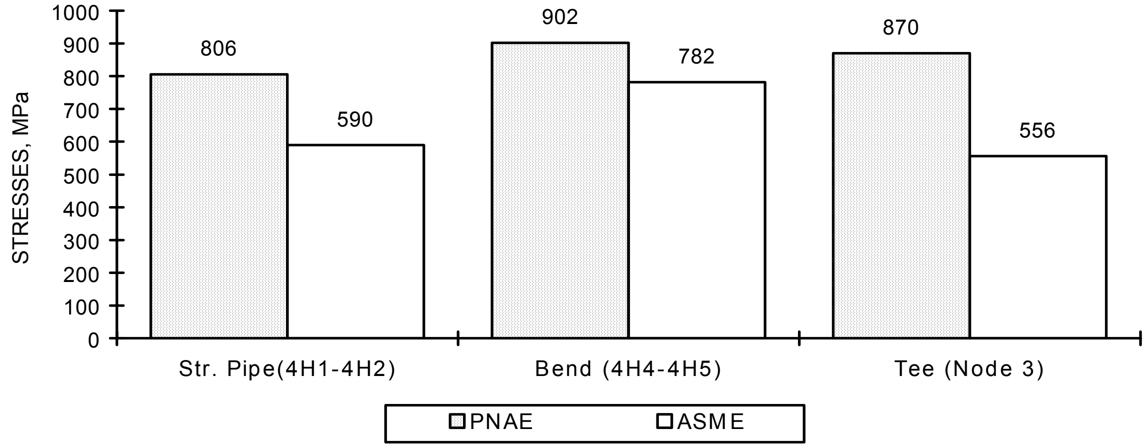


Figure 7 Comparison of stress values for weakest PCLS elements

The higher stress value for PNAE in comparison with ASME BPVC is explained by higher magnitude (about 36 %) of the Response Spectra in the resonance frequency domain.

The ratio between maximal calculated stress values and allowable stresses for the weakest PCLS elements are shown in Figure 8. For PNAE case these values are about 2 times higher than corresponding values for ASME BPVC (2.65/1.45=1.83).

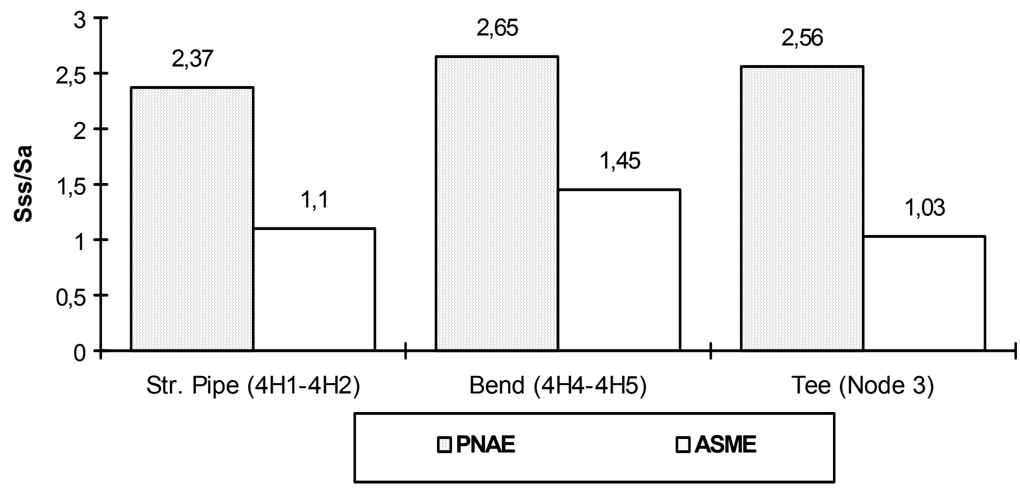


Figure 8 Ratio between maximal S_{ss} and allowable S_a stress values for the weakest elements of PCLS

In recent years the Seismic Margin Assessment Methodology in western engineering practice is widely used /28/. This methodology is based on the analysis of probability of failure for safety-related structures, systems and components. On the basis of Conservative Deterministic Failure Margin (CDFM) the values of High Confidence Low Probability Failure (HCLPF) seismic capacity have to be estimate in terms of maximum earthquake level. Regarding considered pipeline system this value may be defined according to the following equation:

$$HCLPF(CDFM) = \frac{S_a - S_{sl}}{S_{ss} - S_{sl}} \times ZPA.,$$

In this expression the value of HCLPF (CDFM) defines the level of seismic excitation corresponded to the low probability of pipeline failure. ZPA is the maximum intensity of seismic excitation on the pipeline floor level (the value of ZPA is used here instead of ZPGA value in traditional SMA consideration for comparative purposes only).

Figure 9 shows the HCLPF values of seismic capacity for weakest elements of PCLS.

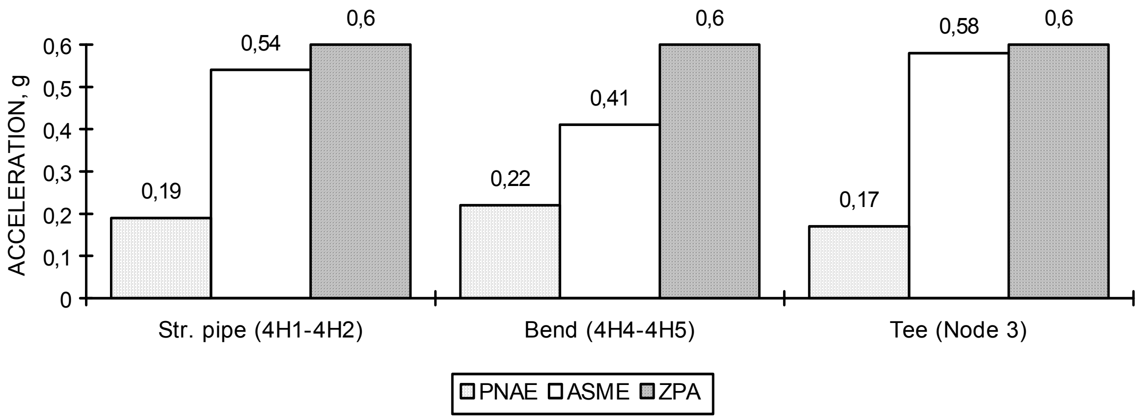


Figure 9 HCLPF values of seismic capacity for selected elements of PCLS (ZPA=0.6g)

For both code cases the minimum HCLPF seismic capacity is lower than input ZPA level equal to 0.6g, that means the seismic resistance of PCLS for considered analysis is insufficient. However, the seismic capacity of system analyzed by ASME BPVC is more than two times higher in comparison with values obtained by PNAE (0.41/0.17 = 2.41).

CONCLUSIONS

1. The basic principals of ASME BPVC, Section III, Subsection NB and Former Soviet (Russian) PNAE as well as some features of Japan JEAG 4601 Code for seismic analysis of NPP piping systems have been considered. Generally all three Codes are practically identical in main principals of seismic analysis of piping system and are in good agreement with IAEA requirements.

2. The principal distinctions between ASME BPVC and PNAE codes are the values of allowable stresses and damping ratio. The requirements of ASME BVPC and JEAG 4601 are much closer in definition of damping values and allowable stresses.

3. The obtained results show that using of PNAE requirements for RSMAM seismic analysis involve essential conservatism for seismic qualification of Class 1 piping systems under SSE (MRZ, S_2) seismic excitation in comparison with ASME BPVC and JEAG 4601. The limit value of piping seismic capacity calculated by ASME BPVC more than **two** times higher than corresponding level for PNAE Code. That means that Class 1 piping system seismic analysis performed by RSMAM and according to demands of PNAE Code satisfies ASME BPVC Class 1 Service Level D requirements.

4. The quantity results and ratios obtained in this study can oscillate significantly depending on material properties, service temperature, pressure and types of pipe elements. Thus, for every certain case it is necessary to carry out individual analysis to make definite conclusion about relative degree of conservatism of each code.

5. The using of TH seismic analysis for Class 1 piping systems, Service Level D leads to essential decreasing of PNAE conservatism against ASME BPVC Codes results due to Codes recommended damping.

6. In cases of analysis Class 2 and 3 piping systems and/or analysis under other than Service Limit D conditions approximately similar or even vice-a-versus effect can be obtained in range of conservatism of PNAE and ASME BVPC both for RSMAM and THA methods.

7. The obtained results can be used for seismic qualification of NPPs designed according to different Codes, Guides and Standards.

NOMENCLATURE

A_s	-	piping cross-sectional area, mm^2;
c	-	total additional wall thickness, mm;
Do	-	nominal outside diameter of pipe, mm;
E	-	Young Modulus, MPa;
I	-	piping cross-sectional moment of inertia, mm^4;
Mi, Mx, My, Mz	-	internal bending and torsion moments, N•mm;
N_s	-	internal axial force due to weight loading, N;
Q	-	piping weight per length, N/mm;
P	-	internal Design Pressure, MPa;
R	-	bend radius, mm;
$R_{p0.2}^T, S_Y^T$	-	minimum yield strength at temperature, MPa;
R_m^T, S_T^T	-	minimum tensile strength at temperature, MPa;
S_Y, S_T	-	minimum yield strength and minimum tensile strength at room temperature, MPa;
S_a	-	allowable stress, MPa;
S_m	-	allowable design stress intensity, MPa;
S_{sl}	-	operation loading stress, MPa;
S_{ss}	-	resultant seismic + operation loading stress, MPa;
s,t	-	nominal wall thickness, mm;
W	-	section modulus of pipe, mm^3;
φ	-	strength reducing coefficient;
[σ]	-	nominal allowable stress, MPa;
$(\sigma)_2$	-	the group of reduced stresses due to mechanical and seismic loading. Defined as combination of membrane and total bending stresses, MPa.

GLOSSARY

AS	-	Emergency Situation;
ASME	-	American Society of Mechanical Engineers;
ASME BPVC	-	ASME Boiler and Pressure Vessel Code;
CDFM	-	Conservative Deterministic Failure Margin;
DBPB	-	Design Basis Pipe Breaks;
HCLPF	-	High Confidence Low Probability Failure;
IAEA	-	International Atomic Energy Agency;
LOCA	-	Loss of Coolant Accident;
MCP	-	Main Coolant Pump;
MRZ	-	Maximum Design Earthquake;
MS/FWPB	-	Main Steam and Feedwater Pipe Breaks;
NNUE	-	Violation of Normal Operating Conditions;
NPP	-	Nuclear Power Plant;
NRC	-	Nuclear Regulatory Commission (USA);
NUE	-	Normal Operating Conditions;
PCLS	-	Primary Coolant Loop System;
PNAE	-	Rules and Standards in Atomic Energy Industry;
RG	-	Regulatory Guides;
RPV	-	Reactor Pressure Vessel
RSMAM	-	Response Spectrum Modal Analysis Method
SG	-	Steam Generator;
SL	-	Sustained Loads;
SMA	-	Seismic Margin Assessment;
SRP	-	Standard Review Plan;
SRSS	-	Square Root of Sum of Squares;
SSE	-	Safe Shutdown Earthquake;
THA	-	Time History Analysis
WWER	-	Water - Water Energetic Reactor
YEU	-	Nuclear Energetic Unit;
ZPA	-	Zero Period Acceleration;
ZPGA	-	Zero Period Ground Acceleration;

REFERENCES

1. Stevenson, J.D., “Standards - Status and Development in the Nuclear Industry”, Proceedings of ASCE Specialty Conference on Design of Nuclear Plant Facilities, Boston, April 1979.
2. Stevenson, J.D. and Thomas, F.A., “Selected Review and Evaluation of U.S. Safety Research Vis-a-Vis Foreign Safety Research for Nuclear Power Plants”, NUREG/CR-3212, US. Nuclear Regulatory Commission, March 1983.
3. Charles H. Hofmayer, Young J. Park, James F. Costello, “Understanding Earthquake Design Criteria Used in Japan”, Proceedings of the Fifth Symposium Orlando, Florida, December 1994. North Carolina State University, Raleigh, NC27695-7908/USNRC/EPRI.
4. “Technical Guidelines for Aseismic Design of Nuclear Power Plants”, JEAG 4601-1987, Japan Electric Association, 1987.
5. ПНАЭ Г-5-006-87. Нормы проектирования сейсмостойких атомных станций. ВГНИКИИ “Атомэнергопроект”, 1988.
6. ПНАЭ Г-7-002-86. Нормы расчета на прочность оборудования и трубопроводов атомных энергетических установок. Энергоатомиздат, М., 1989.

7. ASME BPVC, 1992 Edition, Section III, Division 1, Subsection NB-Class 1, Nuclear Power Plant Components, ASME (1993).
8. ASME BPVC, 1992 Edition, Section III, Division 1, Subsection NC-Class 2, Nuclear Power Plant Components, ASME (1993).
9. ASME BPVC, 1992 Edition, Section III, Division 1, Subsection ND-Class 3, Nuclear Power Plant Components, ASME (1993).
10. ASME BPVC, 1992 Edition, Section III, Division 1, Subsection NF-Supports, Nuclear Power Plant Components, ASME (1993).
11. ASME BPVC, 1992 Edition, Section III, Division 1, Appendix N “Dynamic Analysis Methods”, ASME (1993).
12. ASME BPVC, 1992 Edition, Section III, Division 1, Appendix F “Rules for Evaluation of Service Loading with Level D Service Limits”, ASME (1993).
13. RG 1.29, “ Seismic Design Classification” (Rev. 3, 9/78).
14. RG 1.60, “Design Response Spectra for Seismic Design of Nuclear Power Plants” (Rev. 1, 12/73).
15. RG 1.61, “Damping Values for Seismic Design of Nuclear Power Plants” (Rev. 1, 10/73).
16. RG 1.92, “Combining Modal Responses and Spatial Components in Seismic Response Analysis”(Rev. 1, 2/76).
17. SRP 3.2.1. “Seismic Classification” (Rev.1, 6/81),Report NUREG-0800. NRC, Washington, 1989.
18. SRP 3.2.2. “System Quality Group Classification” (Rev.1, 6/81),Report NUREG-0800. NRC, Washington, 1989.
19. SRP 3.7.1. “Seismic Design Parameters” (Rev.2, 8/89),Report NUREG-0800. NRC, Washington, 1989.
20. SRP 3.7.2. “Seismic System Analysis” (Rev.2, 8/89),Report NUREG-0800. NRC, Washington, 1989.
21. SRP 3.7.3. “Seismic Subsystem Analysis” (Rev.2, 8/89),Report NUREG-0800. NRC, Washington, 1989.
22. SRP 3.9.3. “ASME Code Class 1, 2, and 3 Components, Components Supports, and Core Support Structures” (Rev.1, 6/81),Report NUREG-0800. NRC, Washington, 1989.
23. ПНАЭ Г-7-008-89. Правила устройства и безопасной эксплуатации оборудования и трубопроводов атомных энергетических установок. Энергоатомиздат, М., 1990.
24. ASME BPVC, 1992 Edition, Section II, Materials, Part D, Properties, ASME (1993).
25. ASME BPVC, Case N-411-1.”Alternative Damping Values for Response Spectra Analysis of Class 1, 2 and 3 Piping “. Section III, Division 1, 20.02.1986.
26. Костарев В.В. и др. Разработка методик и программ расчета по обоснованию прочности и сейсмостойкости главных циркуляционных насосов для АЭС с ВВЭР. НПО ЦКТИ отчет No246108/0-11681, Л., 1983.
27. Berkovski A.M., Kireev O.B., Schukin A.J. Analysis and Control Calculations of the Test Pipeline. Stevenson and Associates, Rep.13-95.pks, Plzen, 1995.
28. Masopust R. Guidelines for Seismic Qualification of Technological Equipment of NPP Paks. Stevenson and Associates, Rep.09-92.pks, Plzen, 1992.

APPENDIX

FORMULAS FOR PIPING STRESS CALCULATIONS[1]

1. PNAE Code G-7-002-86 /2/.

1.1. Principal stresses in the pipe cross-section

$$\sigma_3 = \max\begin{Bmatrix} 0.5\left[\sigma_\psi + \sigma_z + \sqrt{(\sigma_\psi - \sigma_z)^2 + 4\tau^2}\right] \\ 0.5\left[\sigma_\psi + \sigma_z - \sqrt{(\sigma_\psi - \sigma_z)^2 + 4\tau^2}\right] \\ \sigma_r \end{Bmatrix};$$

$$\sigma_1 = \min\begin{Bmatrix} 0.5\left[\sigma_\psi + \sigma_z + \sqrt{(\sigma_\psi - \sigma_z)^2 + 4\tau^2}\right] \\ 0.5\left[\sigma_\psi + \sigma_z - \sqrt{(\sigma_\psi - \sigma_z)^2 + 4\tau^2}\right] \\ \sigma_r \end{Bmatrix};$$

where $\sigma_\psi = \sigma_{\psi p}$;

$$\sigma_z = \sigma_{zp} \pm \frac{\sqrt{M_x^2 + M_y^2}}{W} + \frac{N_Z}{A_S};$$

$$\tau = \frac{M_Z}{2W}; \qquad \sigma_r = -\frac{P}{2}.$$

1.2. Tangent and longitudinal stresses from internal pressure

$$\sigma_{\psi p} = \frac{P\left[D_o - 2(s-c)\right]}{2\varphi(s-c)}; \qquad \sigma_{zp} = \frac{P\left[D_o - 2(s-c)\right]^2}{4(D_o - s + c)(s-c)}.$$

1.3. The values of Ω and Ψ are defined by tables Ï.5.1 and Ï.5.2 of PNAE /2/. Also these values may be calculated using following approximate expressions:

$$\Omega = \frac{0.93}{\lambda^{0.755}} \quad \text{when} \quad \lambda \geq 0.05;$$

$$\Psi = 1.0 - 0.0284\left(\frac{\sigma_{\psi p}}{[\sigma]}\right) - 0.29\left(\frac{\sigma_{\psi p}}{[\sigma]}\right)^2 \qquad \text{if} \qquad 0 \leq \left(\frac{\sigma_{\psi p}}{[\sigma]}\right) \leq 1.$$

1.4. For tee pipe elements the values of stress $(\sigma)_2$ category should be considered for three cross-sections: A-A, Б-Б, B-B (see figure Ï5.1 of PNAE /2/).

For cross-sections A-A and B-B

[1] The formulas in this Appendix are given for information and Codes comparative analysis only.

$$\sigma_z = \sigma^O_{zMN} \pm 0.7\sigma^O_{zMN(s)} K_{(s)} + \sigma_{zp};$$

For cross-section Б-Б

$$\sigma_\psi = \sigma_{\psi p} \pm 0.7\sigma^O_{zMN(s)} K_{(s)};$$

$$\sigma_z = \sigma^O_{zMN} + \sigma_{zp}.$$

$K_{(s)}$ -- local bending stress intensity coefficient for tee elements. It is defined according to chapter 2.7 of Appendix 5 PNAE /2/.

1.4.1. Longitudinal stress in the RUN pipe of tee σ^O_{zMN} and in the BRANCH pipe of tee $\sigma^O_{zMN(s)}$ are calculated by the following formulas:

$$\sigma^O_{zMN} = \frac{M_x \sin\Phi - M_y \cos\Phi}{W} + \frac{N_z}{A_s};$$

$$\sigma^O_{zMN(s)} = \frac{\sqrt{M_x^2 + M_y^2}}{W} + \frac{|N_z|}{A_s},$$

where Φ is angle that defined the BRANCH position (see figure П5.1 of PNAE /2/).

<u>2. ASME BPVC, NB-3650, Equation (9) /3/.</u>

2.1. Resulting Moment from static and dynamic loads

$$M_i = \sqrt{M_{xi}^2 + M_{yi}^2 + M_{zi}^2}.$$

2.2. For the tee elements the Equation (9) is written in the following form (NB-3683.1 ASME BPVC /3/):

$$S_{SS} = B_1 \frac{PD_o}{2T_r} + B_{2b}\frac{M_b}{Z_b} + B_{2r}\frac{M_r}{Z_r};$$

where: T_r - nominal wall thickness of designated RUN pipe;
M_r, M_b - resulting internal moments in the run and branch pipes respectively;
Z_r,Z_b - approximate section modulus of designated run and attached branch pipes respectively.

2.3. Stress indices B1 and B2 are defined by the table NB-3681(a)-1:

- For straight pipes: $B_1 = 0.5$ and $B_2 = 1.0$;

- For curved pipes: $B_1 = -0.1 + 0.4h$ if $0.0 < B_1 < 0.5$,
$B_2 = 1.30 / h^{\frac{2}{3}}$ if $B_2 > 1.0$;

- for tee elements B_{2b} and B_{2r} are defined in accordance with NB-3683.8 and NB-3683.9 /3/.

3. Characteristic bend parameter of a curved pipe (elbow):

- <u>ASME BPVC</u> $h = \frac{t_n R}{r^2}$. - <u>PNAE:</u> $\lambda = \frac{sR}{r^2}$;