Transactions of the 17th International Conference on **Paper # K01-5**
*Structural Mechanics in Reactor Technology (*SMiRT 17)
Prague, Czech Republic, August 17 –22, 2003

Russian Regulatory Approaches to Seismic Design and Seismic Analysis of NPP Piping

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ABSTRACT

The paper presents an overview of Russian regulatory approaches to seismic design and seismic analysis of NPP Piping. The paper is focused on categorization and seismic analysis of nuclear power plant items (piping, equipment, supports, valves, but not building structures). The paper outlines the current seismic recommendations, corresponding methods with the examples of calculation models. The paper considers calculation results of the mechanisms of dynamic behavior and the problems of developing a rational and economical approaches to seismic design and seismic protection.

1. INTRODUCTION

The problem of developing a rational and economical approach to the designing of safe and seismic stable piping has been arisen practically simultaneously with the initiation of NPP designs for seismically active areas of Russia, Armenia (former Republic of the Soviet Union).

A number of new temporary regulatory documents [3,4,5] was developed and applied in Russia for piping calculations [1,2] with safety purposes [3,4,5]. The recommendations of above regulatory documents were in compliance with IAEA recommendations [6], ASME recommendations [7,8], referring to basic principles of seismic analysis of piping. But in Russia there were a number of specific recommendations in the part of strength criteria and reliability of piping and equipment components, combinations of seismic loading and damping factors.

Preliminary (temporary) seismic recommendations needed to be verified on the base of experimental and analytical data.

The pilot experimental investigations of physical models of the main circulation loops of NPP with VVER-440 reactor type were carried out in 1973-1975 [9,10 and others] Later on other investigations and tests were performed.

Physical models in scales 1:3, 1:6 and 1:25 were manufactured from different materials used for piping modeling. Heavy equipment was modeled with rigid bodies with due regard to the similarity of mass, moment of inertia, mass centre position in conjunction with the system of supports and hangers. The model tests were performed on vibration tables in resonant mode with electro hydraulic or electro dynamic actuators.

Actual experiments were carried-out at Kola NPP by explosion and impact method in the immediate vicinity (200-300 m. apart) of NPP reactor building.

The oscillations were observed in the primary circuit and dynamic characteristics (frequency of 2-th mode of damping) were determined.

These results were further applied for verification of calculation methods and calculation programmes.

Experiments investigation is a very expensive method to study a dynamic behavior of NPP piping.

Experimental studies were mainly concentrated on the determination of dynamic characteristics of equipment, on verification of calculation models and approaches as well as on reliable demonstration of active and passive devices functioning in case of earthquake.

At the same time NPP includes plenty of pipelines important for safety. They must be safety in cases of earthquake, but their analysis shall not be expensive.

The construction of the first NPP in Armenia has put into the number of the most important tasks the creation of methods and programmes for determination of oscillation parameters, calculation of piping seismic strength and selection of the seismic protection systems, including their verification on the base of analytical calculation methods.

2. GENERAL APPROACH TO SEISMIC STABILITY INVESTIGATION OF BUILDING STRUCTURES

The comprehensive approach to investigation of seismic stability of building structures can be divided into four main stages:

2.1. Determination of basic parameters of ground vibration on NPP site.
2.2. Analysis of grounds and building structures interaction and dynamic analyses.
2.3. Determination of response spectrum on NPP overlapping, of support and equipment loading points.
2.4. Seismic strength analysis of NPP piping.

The above mentioned complete calculation analysis was carried out for units 1 and 2 of Kalinin NPP [12]. This paper focuses only on stage four.

3. INFORMATION ON PIPING

NPP piping operate under complex loading conditions, caused by the effect of pressure, gravity, temperature – induced forces, high temperatures and unsteady operating modes. In the majority of cases the NPP pipelines comprise branching systems with a large number of intermediate supports, ells, T-joints and pipeline fitting.

Each piping system, with its certain position in the processing line, contributes to NPP safe operation. One of the basic objective of design is to prevent damage of piping components in cases of earthquakes as a result of significant increase of permissible tolerable stress level in one or several sections because of collisions resulting from the exceeded level of tolerated displacements or exhausted durability reserve. The pipeline oscillations resulted from an earthquake at the background of damages accumulated as a consequence of operational loads may cause violations during the earthquake. Along with the pipelines, the resistance requirements are also imposed upon the equipment comprising part of the "equipment – pipeline-equipment" technological systems. Basically, they amount to the requirements of mutual elimination of excessive force carried upon both piping and equipment.

4. MODELING OF PIPING

AS there is a definite interaction between equipment and piping, the dynamic calculation model of the pipeline system is developed with the account of this factor. But practically this factor is not always correctly accounted in calculations.

The piping-to-equipment attachment points are taken as restraints or as rods of specified pliancy.

At the same time the equipment can significantly impact on piping components and form in them a compound stress. Modeling of equipment is to a greater extent determined by the method potentialities and its realizing program of the automated calculation in comparison with piping. Upon substantiating of equipment seismic stability and its unfastening, it is allowed to perform test calculations of piping seismic strength without including them into the equipment design model.

If it is allowed by calculation program, the inclusion into the design model of the components, simulating the equipment, makes it possible to obtain more accurate results due to the account of interference of equipment and piping. Since the substantiation of piping seismic stability is realized by calculation methods, the construction of design dynamic models attracts significant attention.

5. MATHEMATICAL MODEL

Seismic analysis needs the following:

5.1 Mathematical modeling of oscillations.
5.2 Solution of the tasks of static analysis, dynamic analysis, response spectrum analysis.
5.3. Account of damping.

An equation of motion of centre of mass of mathematical model as digital mass number is described by an equation of matrix type:

$$[A]\,[M]\,\ddot{U} + [A]\,[C]\,\mathring{U} + U = [A]\,[M]\,\ddot{W},$$

where [A], [M], [C] – are correspondingly matrices of pliancy, masses and damping.
U, $\mathring{U}$ and $\ddot{U}$ – are vectors of acceleration of velocities and travels.
$\ddot{W}$ - is a vector of seismic impact acceleration.

The dynamic solution of this differential equation can be achieved by different ways: handbook calculations, computer simulation via programming, or by the more commonly used method of finite element computer modeling.

Any of applied methods, realizing a mathematical model, is the most important part of the analytical process. It is essential, when the model is supported by dynamic characteristics of building structure components. The frequency of natural oscillations is determined by calculation results during the solution of equation with the condition, that seismic oscillations and damping at the system are equal to zero.

$$[A]\,[M]\,\ddot{U} + U = 0$$

6. METHODS OF DETERMINATION OF OSCILLATION PARAMETERS OF PIPING

In the last years several versions of methods for determining oscillation parameters of piping and equipment during dynamic loads have been developed. Fig.1 shows a block-diagram for synthesizing the programme algorithms, applied for calculation of oscillation parameters and for piping seismic reaction [13].

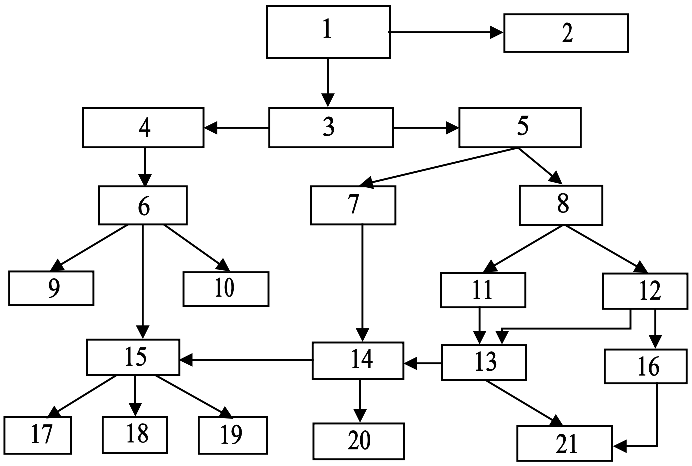

Fig. 1: Block-diagram for synthesizing the program algorithms employed for evaluating seismic resistance of the APP technological systems, where: 1 – Methods of calculating the APP pipelines for seismic loads; 2 – statistical METHOD; 3 – method of dynamic analysis; 4 – Analysis of effect parameters (accelerogram); 5 – analysis of the pipeline system inherent parameters; 6 – Finite difference method (FDM); 7 – Method of transfer function matrix; 8 – Method of large matrix; 9 – Runge-Cutt method; 10 – Implicit Wilson difference method; 11 – Rod model in the form of material point system; 12 – Finite element method; 13 – solution of inherent values problem; 14 – Method of instantaneous values (accelerogram); 15 – Method of initial values; 16 – Partial problem of inherent values; 17 – Packard method; 18 – Bash fort-Adams method; 19 – Tailor expansion into a series method, etc.; 20 – Express method of numerical integration (Duhamel integral); 21 – Linear-spectrum method (response spectrum).

During statistic calculations the design models are considered, describing piping arrangements.

Application the dynamic method analysis (DMA) requires, as a rule, not only modification of the calculation diagrams, but the development of special design dynamic models, and preparation of a special assignment for computer. Besides, in the majority of cases it is necessary to carry out special investigations considering the inertial characteristics, damping, friction of structural components incorporated in calculation models, and analyze the impact of refined and discarded connections, etc. The programmes of dynamic calculations, performed in Russia (former the Soviet Union) for substantiating of seismic resistance of complex process systems and piping, are synthesized with combinations of various methods. This widespread development of methods and programmes resulted from a large-scale designing and construction of NPPs in seismically active areas in 70-80 years. The programs have been developed for large-scale computers installed in some organization of Russia. There are as follows: “Astra-Seism”, “EAS-82”, SEISM-282, STADIAS, STADIAS, KMC, etc. They allow to use accelerogramme and response spectra in calculations. In the recent years the above and other programmes have been developed for present-day computers.

In order to reduce the labour-intensiveness of design calculations for NPP piping in Russia, along with precise methods the simplified ones were developed for evaluation of seismic strength at the early stages of process systems design as well as an engineering procedure [14], determining the seismic reaction of piping and the equipment included into the calculation model during the analysis of only low forms of its structural member vibrations. This engineering methodology was widely implemented design practice. The methodology contains recommendations on determination of natural oscillation frequencies, formulae for determining seismic reaction in the form of stresses, travels and efforts in support components and on pipe taps, selection method of seismic protection, evaluation methods of strength fatigue with consideration of a number of cycles of stress amplitudes of various level obtained by piping during NPP operation. The engineering methodology allows to use static calculation programme potentialities.

Calculation substantiation of seismic strength in accordance with regulatory approach and categorization by seismic stability of piping is realized with application of response spectrum for the marks of installation of cradle beddings of piping and equipment, included to the calculation model or for the mark of building structure base with the account of dynamic coefficients of corresponding type of respective building structures up to the required mark [15,16].

7. EXAMPLES OF CALCULATION MODELS

As an example, illustrating the approach to the construction of the design dynamic models, a description of the piping construction in the multiple-forced circulation loop in pressure-tight rooms and of engines of the main circulating pumps of NPP with RBMK reactor-type is given.

Fig. 2 shows the model calculation diagramme incorporating: a suction (SM) and pressure (PM) manifold, two main circulating pumps (MCP), Dy - 300 fixed passage-to-SM incisions pipelines, Dy - 300 PM-to-fixed supports (installed not far from the distributing group manifold) pipelines, four SM-to-MCP and MCP-to-PM pipeline branches, valves and support components of various types.

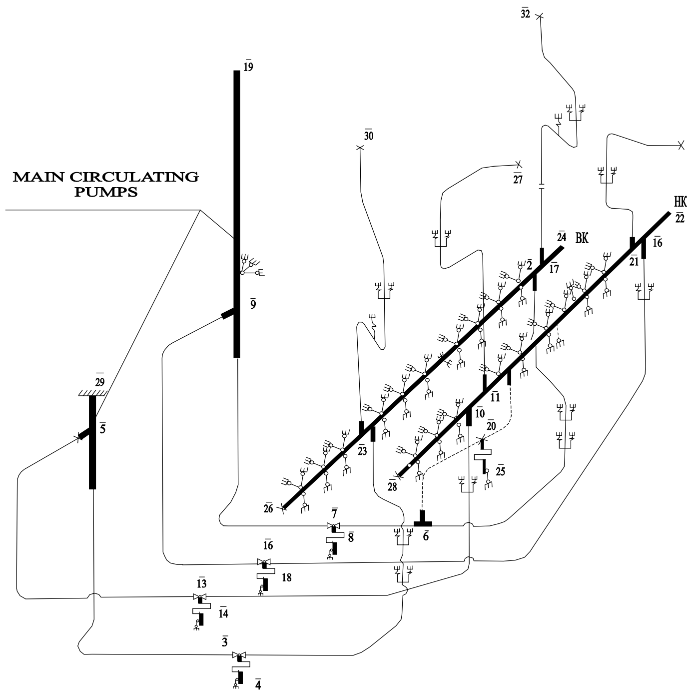

Fig. 2: Calculation diagram of pipelines in the multiple-forced circulation loop of the pressure-tight rooms, as well as in the rooms of engines of the APP HPCR main circulating pumps.

The diagramme includes a PM-to-SM connector. The pressure and suction manifolds comprise horizontal cylindrical vessels. The manifold is rigidly attached to fixed supports with its ends – on the slipping supports.

Calculations account the MCPs mobility, their impact on the dynamics of the entire loop. The Dy – 800 of MCP to SM and from PM to MCP pipelines mount elastic supports, including four of them are of complex design and large load capacity. The support component has a symmetrical construction, consisting of four components, each having two springs of differing characteristics. Inside the spring there is a cylindrical sleeve. A four-component assembly is placed into a special framework, capable to move in a horizontal plane and in two mutually perpendicular directions. The operational features of the support have been considered during its modeling with various load levels.

8. ANALYSIS OF SEISMIC REACTION

During the assessment of seismic stability the indicated stresses are used, which are determined for various time periods based on essential stresses for all operation modes, including the violations of operating conditions, test conditions, and seismic loads.

In seismic stability analysis of piping the indicated stresses are determined according to the amount of the components of common or local membrane, of common or local bending, of common or local temperature and compensatory stresses, of common membrane and common bending of seismic loads with the account of stress concentrations.

Subject to analysis of the seismic strength both by the dynamic and static methods are the pipelines that have passed through the design and strength evaluation stages under the impact of static and cyclic loads.

The seismic strength evaluation of process systems is performed with requirements [15,16,17].

9. SEISMIC PROTECTION

The basic principles of arrangement and fastening of primary circuit equipment of NPP with VVER reactor type.

To fulfill the requirements [3,4], the support structures for equipment and piping of MCP must restrain their travel at any seismic effect. An earthquake-proof fastening with support structures, designed for carrying operational loads will reduce seismic response to a minimum, providing that the seismic protection does not impede normal functioning of the equipment. In many respects the location and design of earthquake-proof supports are conditioned by the arrangement patterns.

In the accepted arrangements of the primary circuit of NPP with VVER reactor-type the reactor is fixed on a supporting ring girder of a concrete pit. The reactor shell has a clamp ring under the branch pipes and a support ring, placed on the circular girder. The vessel is fastened with radial keys that prevents from its turning movement and at the same time does not hamper thermal expansion of the vessel and straps, restraining vertical displacement of the reactor. The reactor vessel is additionally fastened in the vicinity of the main connector flange. This fastening is structurally intended to bear horizontal loads.

Analysis of the reactor assemblies strength against seismic impact has proved the importance to fasten jackets of the drives and metal work of the reactor cover in horizontal direction. The drive jackets are secured with wedges placed between the jackets and spacing grates. The metalwork is fixed by mounting of service floor in such a way that no clearance is left between the floor and the roof metalwork.

This design of the reactor vessel fastening is admitted irrespective of the site seismicity which means that it may be considered rigid when evaluating seismic safety.

No circulation loop equipment is held up by rigid supports. Horizontal steam generators are mounted on hinge hangers allowing certain deviations and turning of the steam generator, or else on rolling-contact bearings. The rolling-contact bearing of the head circulation pump does not restrain its horizontal displacement. All circulation loops are similar in configuration.

The pipelines of volume compensation in primary circuit and pipelines of the fuel core emergency cooling system are considered to important for safety. They ensure self-compensation of thermal expansions due to strength matters. This is the reason for fixing rigidly the volume compensator and water tank of emergency water supply of the reactor with a cylinder shell welded to the bottom and bolted or welded to the inserts of building structure.

Additional seismic protective supports of the volume compensator and of the emergency core cooling system water tanks are manufactured in the form of rods either hinged to the vessel and walls, or to the building ceilings.

With the purpose of making steam generators, main circulating pumps, main locking valves, fitting and piping resist seismic loads, hydraulic dashpots are set up, which number, power, place of installation are being conditioned by the design analysis of different variants. Seismic protections of MCP of NPP with VVER-440, VVER-1000, of ECCS piping and piping system of volume condenser [12,18] were determined.

However, installation of hydraulic dashpots, especially on NPP primary circuite systems means additional expenses on their operation, mainly on specified operations to maintain their working condition in accordance with technical characteristics. The objective of optimal seismic safety design of primary circuit is to provide the strength and reliability of the systems safety at minimal costs of seismic protection. Optimization of seismic safety design as applied to a given site, is to be based on dynamic analysis method, and dynamic models, including interrelated equipment and piping, reactor, support structures, dampers, etc. [19].

Detailed analysis of mode parameters consists of studying of mode shapes, determining seismic response in sections and support components, including maximum displacement level test to impede intercollisions and collisions with special supports aimed in the primary circuit as a kind of protection against MCL pipe rupture, study of the level of seismic acceleratios aristing in equipment, variants of the case of hydraulic dashpots fallen out of operation. Seismic safety optimization design is conducted by dynamic analysis of seismic impact, specified by calculation accelerograms,whch charaterise the seismicity of NPP site, response of NPP building construction with the account of its interaction with earth foundation.

The loads on internal units of these systems are determined by the way of solution of nonlinear problems. As in the case of the main circulations pump, the connections between the pump and motor; steam generator body and piping are presented as the elements of dissipative-elastic forces.

As the result of the studies on optimization of seismic protection for MCP of NPP with VVER-440 and VVER-1000 the protection schemes were developed.

10. CURRENT PROBLEMS OF SEISMIC STABILITY OF PIPING

The problems of substantiating of seismic resistance of NPP piping are being constantly developed and improved. The main attention is paid to the substantiation of the methods of calculation, software and design models. One of the main problems is damping.

At present the calculation substantiating of seismic stability of NPP process systems is carried out with very low damping values in piping. To avoid conservatism referring to the applied values of damping the directive approach to the increase of damping can not be accempable. This problem is to be experimentally investigated.

The other problems to study are the effect of the plastic hinges formation on the piping dynamic characteristics and evaluation of the strength reserves under the loads as a random time process with a sufficiently low probability of system loading with forces of maximum design intensity.

11. CONCLUSION

This paper includes a summary of regulatory and methodological approaches to seismic design and seismic analysis of NPP piping in Russia.

Though the earthquakes are determined on the base of probabilistic approaches, seismic analysis, seismic design and seismic protection are to be considered deterministically. Probabilistic approaches to seismic protection analysis may be useful for the decrease of risks in case of eqrthquakes.

For new designed and constructed NPPs it is important to apply analytical and experimental methods of seismic analysis. Experimental analysis will allow th exclude conservatism in damping.

The developed principles of NPP piping modeling and calculation methods, realised, as it was mentioned above, as different programmes are widly implemented in design.The experience of substantiation and earthquake proofing of equipment and piping has been accumulated for a number of domestic and foreigh NPPs. For resent years the international experience has being considered at Russian NPPs.

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