SELECTION CRITERIA AND CODE QUALIFICATION OF PIPING SYSTEMS IN A NUCLEAR FUEL CYCLE FACILITY

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ABSTRACT

The process operations of a nuclear fuel cycle facility are complex and involve handling of radioactive material. Process systems are installed inside shielded concrete Cells. These process systems includes large amount of piping. A nuclear fuel cycle facility at Kalpakkam, India has more than 6000 piping spools which lead to about 100 kms of total piping inside the concrete cells. Piping is very dense due to limited cell space and intensive efforts are required in designing their layouts. The piping caters to variety of plant requirements and is classified as Nuclear Safety Class 2 components. All pipelines and their supports have to meet the requirements of ASME B&PV Code, Section III, Division 1-Subsections NC and NF. Designer has to consider sustained, thermal and occasional seismic loads for design.

It would be a very tedious and time consuming job to model and analyze each piping spool. Such approach would also increase the design cost and hamper the project schedule. Hence few representative lines have to be judiciously selected for analysis and code qualification in order to prove the safety of entire piping. The objective of this paper is to discuss the criteria which have been formulated to select sample pipe lines for stress analysis and methodology used for code qualification of piping. This paper further discusses the results of code qualification for the nuclear fuel cycle facility at Kalpakkam.

INTRODUCTION

Nuclear fuel cycle facilities are an important part of the three stage nuclear power program of India. One such facility is currently under construction at Kalpakkam, India. The design of nuclear fuel cycle facility at Kalpakkam is the most recent one wherein all the design and operation feedback from the previous facilities have been incorporated. The process operations of these facilities are quite complex and involve handling of radioactive material. These operations are carried out inside the compact shielded concrete cells. Each plant has four to six such cells. A typical cell has length of 10.5 m, width of 9 m and height of 18 m. Design of various systems for such facilities have always been very challenging. One of the critical areas in mechanical design is the design and code qualification of piping systems for such facilities.

There are over 400 process equipments housed inside the cells to perform the process operations. The required piping for such facilities is quite complex and large in length. The total length of piping inside the six cells of nuclear fuel cycle facility at Kalpakkam is about 100 km. Intensive efforts are required by the designer to plan a very systematic layout for the piping in the limited cell space. Piping is very dense and common pipe supports needs to be planned instead of independent supports. Many pipelines are subjected to high temperature during operation, whose flexibility requirements have to be satisfied to limit thermal stresses. At the same time seismic loads are also significant for such plants. Designer has to ensure that thermal and seismic deflections will not result in pipelines causing an impact on closely spaced adjacent pipes.

In-cell piping has been classified as nuclear safety related piping. Hence it is the responsibility of the designer to ensure that all pipelines meet the stringent requirements of ASME code for stress control. To calculate stresses in the piping due to various loads like sustained, thermal and seismic, detailed finite element analysis is required. Modeling, analysis and code qualification of the entire in-cell piping is a tedious job due to its large quantity. For instance the Kalpakkam facility has about 6000 pipe spools inside the cells. If all these spools were to be modeled, analyzed and checked for code conformance, design cost would have increased by several times and time required to do so would have hampered the project schedule. Hence few representative lines have to be judiciously selected for the analysis and to have a code qualification in order to prove the safety of entire piping. Thus, the onus on the piping designer is to have a good layout planning, meet the safety norms, provide economical solutions and meet the project schedule.

The objective of this paper is to discuss the criteria which have been formulated to select sample pipe lines for stress analysis and methodology used for the code qualification of piping.

PIPING SYSTEMS

Each process cell houses variety of equipments and associated piping systems. The equipments include pulse/ion-exchange columns, heat exchangers (evaporators & condensers), scrubbers, chillers, storage tanks, etc. These equipments are supported at different elevations inside the cells through a frame work of steel structural beams and columns. Pipe lines inside the cells are process lines, steam lines, compressed air lines, cooling water lines, off-gas lines, chemical lines and instrumentation lines. Pipe material is Stainless Steel 304L and pipe sizes range from DN 6 to DN 300. Piping layout has been prepared with exhaustive planning so as to accommodate such a wide variety and large amount of piping in the confined cell spaces. Nevertheless limited space has resulted in very dense and complex piping. Pipe to pipe spacing have been optimized based on the analysis results.

Pipelines generally run in groups/tiers with common structural steel members supporting it at appropriate spans. Pipe support members are of SS 304L and are welded to staging members or to embedded plates provided on cell walls at suitable locations. A variety of pipe supports have been provided. Typical supporting arrangement for piping is shown in figure 1. U type clamps are provided to restrain the pipelines. The supports which need periodic maintenance such as spring hangers, snubbers, etc. have not been used inside the process cells since there is no accessibility to them after the plant comes to operation. Pipelines enter inside the cells through embedded pipes introduced with the civil structure. Pipes are butt welded to equipment nozzles inside the cells. The maximum pressure and temperature occurs in steam lines which is 9 bars and 175^{o}C respectively. The flexibility requirements of piping have been taken care of by providing sufficient number of bends with appropriate radius of curvature.

Based on its significance towards nuclear safety, this piping has been classified as safety class 2 components. Hence, it has to meet all the safety requirements of ASME Boiler & Pressure Vessel Code, Section III, Division 1, subsection NC. Pipe supports have to meet the requirements of subsection NF.

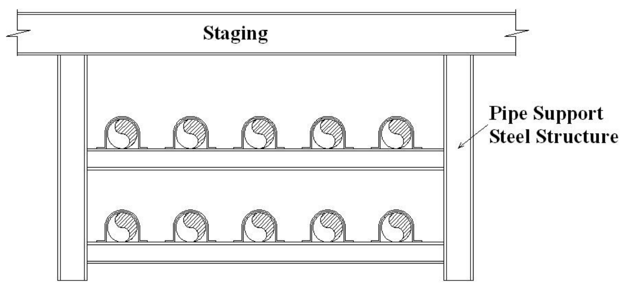

Fig 1: Typical pipe support arrangement inside process cell

SELECTION CRITERIA

As already mentioned there are over 6000 different types of pipe spools which were to be checked for conformance to ASME code. Stresses due to various loads such as dead weight, pressure, temperature and seismic loading have to be maintained within the allowable stresses permitted by the code. However, it was practically not possible to model and analyze all these pipelines for stress calculation. Thus few representative pipe lines have been selected for stress analysis and code qualification. This was done based on the following criteria.

a) Piping With Thermal Loads

The pipelines inside the cells with thermal loads are steam lines, off gas lines and cooling water lines. Steam lines are of two types, high pressure steam lines and low pressure steam lines. High pressure steam lines supply steam to ejectors to transfer process fluids. Low pressure steam lines are meant for various heat exchangers like thermo-siphon evaporators. Off-gas lines are required to maintain vacuum inside process equipments. Governing loads on these lines are weight, pressure, temperature and seismic loads. Since the flexibility requirements for thermal and seismic loads are contradictory in nature, design of these pipelines is very challenging task. Balance between thermal and seismic stresses needs to be obtained by proper layout.

These pipelines were first categorized into various groups based on the similarity in their layout. Each group was made with pipelines of same size but with different lengths. A supporting scheme was planned for each group. Then from each group at least two lines were selected for modeling, analysis and code qualification. One line was selected with shortest lengths between the bends so as to have the least flexibility within that group. If it meets the thermal stress requirement of the code, all remaining lines from the group will also qualify for these requirements. The second line which was selected was of largest lengths between the bends. This line being the most flexible line among the entire group will be critical from seismic considerations. An additional line was also selected from seismic considerations if it was found during the analysis that fundamental frequencies of second selected line were below the peak regions of response spectra in three directions. The additional line if required was selected such that it has fundamental frequencies at the peak regions of response spectra.

Thus, qualification of these pipe lines for all the loads will automatically qualify all the pipelines in the group. Any changes in the supporting scheme based on analysis results were extended for all the pipelines in the group.

b) Piping Without Thermal Loads

Chemical, air and water pipe lines inside the cells do not have any thermal loads. Dead weight and seismic loads are the only governing loads for them. It was decided to support these pipelines with spans depending on their sizes as per table 1.

Table 1: Maximum support span

Pipe Size	Maximum support span
Size ≤ DN 50	2 m
DN 50 < Size ≤ DN 100	3.5 m
DN 100 < Size ≤ DN 300	4.5 m

The common supporting spans for the range of sizes have helped in providing common structural pipe supports and thus reducing number of pipe supports inside the process cells. This supporting scheme has been found to be adequate for limiting sag (vertical deflections) in pipes and stresses due to dead weight. Most of the lines have a continuous slope towards the destination tank for draining after the transfer operation. Thus the sag is limited to avoid any hold up in the lines after the fluid transfer. The supporting criteria for limiting sag and stresses due to dead weight are adequate to take care of seismic loads. To validate this supporting scheme, these pipelines were first segregated into various groups with each group having lines of same type (i.e. water pipe lines, chemicals pipe lines, etc) and same size. Sample pipelines were then selected randomly from each group for detail stress analysis and subsequent code qualification.

Based on the above selection criteria, 499 pipelines were selected out of 6000 pipelines for detail stress analysis and code qualification.

DESIGN AND SERVICE LOADS

Various loads on the piping system have been categorized based on the codal requirements as follows.

Design Loads

The design pressure, design temperature and design mechanical loads have been calculated from maximum loads defined in service level A condition.

Service Level A Loads

This service level includes pressure, temperature and mechanical loads due to normal operation conditions. For the piping systems of this nuclear facility two operating conditions have been considered, start up and shut down. For startup condition, operating pressure and temperature have been defined by process engineers for various pipelines. Mechanical loads for startup condition include self weight of pipelines and weight of contents.

Service Level C Loads

This service level includes occasional seismic loads. The design basis earthquake considered for this facility is a site specific earthquake having a return period of 10,000 years. The peak ground acceleration value for such an earthquake for Kalpakkam site is 0.156g (g is acceleration due to gravity).

FINITE ELEMENT ANALYSIS

A detailed finite element analysis was carried out using piping analysis software CAEPIPE. A typical finite element model prepared using this software is shown in figure 2. The modeling was done using straight pipe and bend elements inbuilt in the software [1]. Each node of these elements has six degrees of freedom i.e. three translations and three rotations. All the six degrees of freedom were fixed at anchor locations, whereas at pipe support locations only lateral deflections were fixed.

This analysis consists of following parts:

(i) Static analysis was done to evaluate deflections and bending moments due to sustained loads i.e. design pressure and design mechanical loads.

(ii) Static analysis was done to evaluate deflections and bending moments produced due to thermal expansion when piping system goes from shut down condition to start up condition.

(iii) Eigen value analysis was performed to calculate natural frequencies and mass participation factors of the pipelines.

(iv) Response spectrum analysis was performed to evaluate responses due to inertial seismic loads. The response spectrum used for the analysis is the envelope of individual floor response spectra at piping support locations for 5 % damping. The envelope response spectra used for the analysis are shown in figures 3a, 3b & 3c for the three directions. Response spectrum analysis was performed independently in three directions considering modes up to natural frequency of 33 Hz. Missing mass correction was applied to consider effects of response due to modes having frequency greater than 33 Hz. 10 % SRSS method of modal combination was used to combine responses due to various modes. To combine response of all three directions, SRSS method of spatial combination was applied.

(v) Static analysis was performed to evaluate forces and bending moments due to seismic anchor motions.

To evaluate stresses in the supports, finite element analysis of supports was carried out using software NISA.

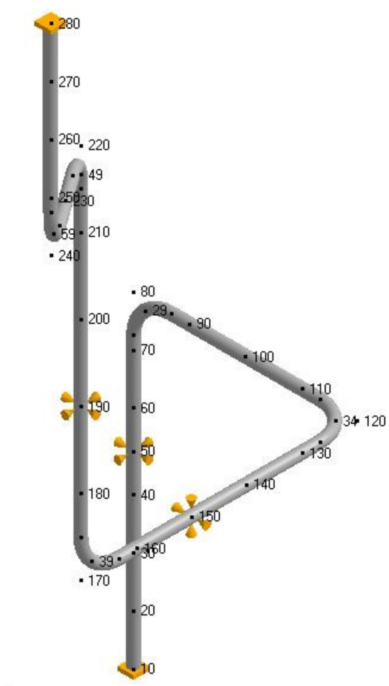

Fig. 2: A typical finite element model of pipeline

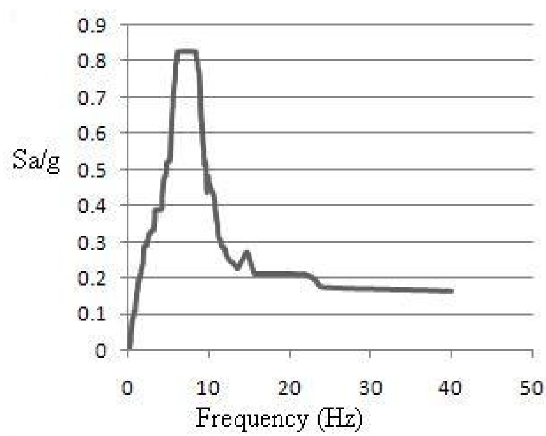

Fig. 3a: Response spectrum in X (hor.) direction

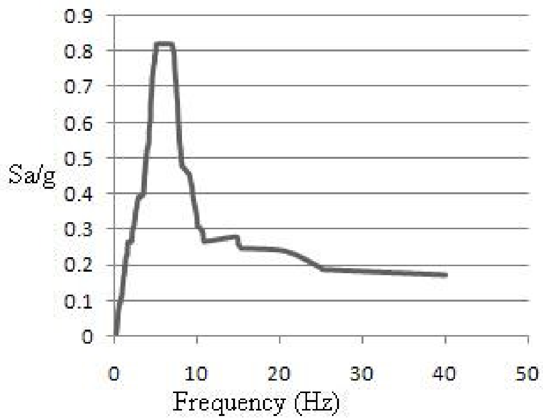

Fig. 3b: Response spectrum in Y (hor.) direction

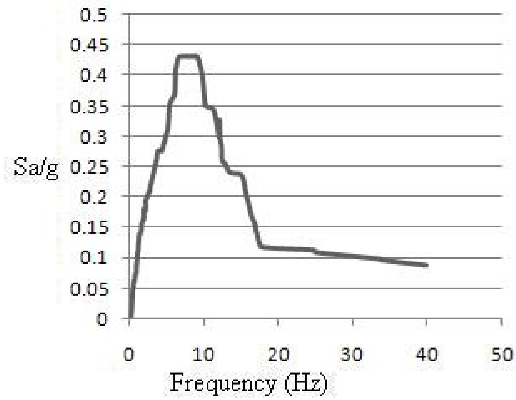

Fig. 3c: Response spectrum in Z (ver.) direction

CODE QUALIFICATION

Piping inside the process cells is nuclear safety related and is classified as Safety Class II components. Design has been carried out as per the provisions of ASME BPV Code, Section III Division 1, Sub section NC. The outputs of the stress analysis have been used to check the equations of the code. The governing equations of the code are described below [2]:

Design Condition

The minimum thickness of straight pipe is given by,

$$t_m = \frac{PD_o}{2(S + Py)} + A \tag{1}$$

where P is internal design pressure, D_o is outside diameter of pipe, S is maximum allowable stress for material at design temperature, A is additional thickness provided for corrosion & erosion, y is coefficient having a value of 0.4 except that for pipe with D_o/t_m ratio less than 6 the value of y shall be taken as $d/(d+D_o)$, and d is the internal diameter of pipe.

The nominal thickness (t_n) of the pipe should be greater than (1.08/0.875)t_m. The factor 0.875 takes care of manufacturing tolerance of 12.5 % on nominal thickness [3] and factor 1.08 allows for 8 % additional thickness to account for thinning which occurs while preparing $5D_o$ bends.

The effects of pressure, weight and other sustained mechanical loads shall meet the following equation.

$$S_{SL} = B_1 \frac{PD_o}{2t_n} + B_2 \frac{M_A}{Z} \leq 1.5 S_h \tag{2}$$

where B_1 & B_2 are primary stress indices, M_A is the resultant moment loading on the cross section due to weight and other sustained loads, Z is section modulus and S_h is basic material allowable stress at design temperature.

The Eq. 1 and Eq. 2 defined above deals with primary type of stresses which can cause failure in the piping within a single application of load.

Service level A

The effects of thermal expansion when system goes from one operating condition to other shall meet the following requirement.

$$\frac{iM_C}{Z} \leq S_A \tag{3}$$

where M_c is the range of resultant moments due to thermal expansion and thermal anchor motions at equipment nozzles, i is stress intensification factor and S_A is the allowable stress range.

Thermal stresses are secondary in nature and can cause failure of piping only due to cyclic operations. The allowable stress range thus depends upon number of cycles of operation and is given by following expression.

$$S_A = f(1.25S_C + 0.25S_h) \tag{4}$$

where S_c is the basic material allowable stress at minimum temperature and f is the stress range reduction factor depending on number of cycles of operation. Value of f is 1.0 if number of cycles of operation is less than 7000 and it reduces for higher number of cycles. For this facility, number of cycles of operation has been estimated to be less than 7000. Hence, the value of f used is 1.0.

Eq. 5 defined below may be checked instead of Eq. 4.

$$S_{TE} = \frac{PD_o}{4t_n} + 0.75i\left(\frac{M_A}{Z}\right) + i\left(\frac{M_C}{Z}\right) \leq (S_h + S_A) \tag{5}$$

where 0.75i shall not be less than 1.0

Service level C

Service level C loads include reversing type of dynamic loads such as earthquake loads. Hence, following conditions must be satisfied.

(i) The pressure occurring coincident with earthquake loads shall not exceed the design pressure.

(ii) The sustained stress due to weight loading shall not exceed the following

$$B_2 \frac{D_o}{2I} M_w \leq 0.5S_m \tag{6}$$

where M_w is the resultant moment due to weight effects, I is moment of inertia and S_m is allowable stress intensity at design temperature.

(iii) The stress due to weight and inertial loading due to earthquake (reversing dynamic loads) in combination with the level C coincident pressure shall not exceed the following

$$B_1 \frac{P_C D_o}{2t} + B_2' \frac{D_o}{2I} M_E \leq 2.1S_m \tag{7}$$

where P_c is the pressure occurring coincident with the earthquake loads, B_2' is the primary stress index and M_E is the resultant moment due to the inertial loading from the earthquake.

(iv) The range of the resultant moment M_{AM} and the amplitude of the longitudinal force F_{AM} resulting from the seismic anchor motions (SAM) shall not exceed the following

$$C_2 \frac{M_{AM} D_o}{2I} \leq 4.2S_m \tag{8}$$

$$\frac{F_{AM}}{A_M} \leq 0.7S_m \tag{9}$$

where C_2 is the secondary stress index and A_M is cross-sectional area of metal in the piping component wall.

(v) Piping displacements shall satisfy the design specification limits.

Pipe supports as shown typically in figure 1 have been classified as linear type of supports and qualified as per ASME BPV Code Section III, Division 1, Sub section NF. Support members have axial tension plus bending type of stresses. These stresses have been checked as per following equation of the code for Design/Service Level A loads.

$$\frac{f_a}{0.60S_y} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}} \leq 1.0 \tag{10}$$

where, f_a is the computed direct axial tensile stress, S_y is the yield strength of material, f_{bx} & f_{by} are computed bending stresses about major and minor axis of cross section respectively, F_{bx} & F_{by} are allowable bending stresses about major and minor axis respectively in the absence of axial stress. Value of F_{bx} & F_{by} is $0.66S_y$ as per the code. For service level C loads which include seismic loads, allowable stresses are increased by 50 %. Hence R.H.S. of equation 10 becomes 1.5.

RESULTS

CAEPIPE software has an inbuilt capability to check the equations 1 to 9 at all the nodes of the piping. Equation 10 for supports has been checked manually based on axial and bending stress values obtained from finite element analysis of supports on software NISA. The tables 2, 3 & 4 show the summary of code qualification results. The stress values in tables 2 & 3 are the maximum values from the analyzed pipelines [4] and hence each stress value may be applicable for different pipeline.

Table 2: Code qualification results of piping for Design & Service Level A loads

Pipe Thickness (Eq. 1)		Sustained Stress (Eq. 2)		Thermal stress (Eq. 3 & 4)	
Minimum t_m	Available $(0.875/1.08)t_n$	Maximum S_{SL}	Allowable $1.5\ S_h$	Maximum $(i.M_c/Z)$	Allowable S_A
1.13 mm	2.73 mm	66.9 N/mm^2	167.8 N/mm^2	99.5 N/mm^2	139.1 N/mm^2

Table 3: Code qualification results of piping for Service Level C loads

Sustained stress due to weight (Eq.6)		Stress due to weight & inertial loads from earthquake (Eq.7)		Bending stress due to SAM (Eq. 8)		Longitudinal stress due to SAM (Eq.9)	
Maximum	Allowable	Maximum	Allowable	Maximum	Allowable	Maximum	Allowable
42.8 N/mm^2	57.5 N/mm^2	146.2 N/mm^2	241.5 N/mm^2	293.0 N/mm^2	483.0 N/mm^2	5.1 N/mm^2	80.5 N/mm^2

Table 4: Code qualification results of pipe supports

Computed stress to allowable stress ratio (Eq.10)			
Design / Service Level A		Service Level C	
Maximum	Allowable	Maximum	Allowable
0.32	1.0	0.39	1.5

Figures 4a & 4b shows the thermal stress plot and sustained plus inertial seismic stress plot obtained from Eq.3 & Eq.7 respectively for the typical model shown in figure 2.

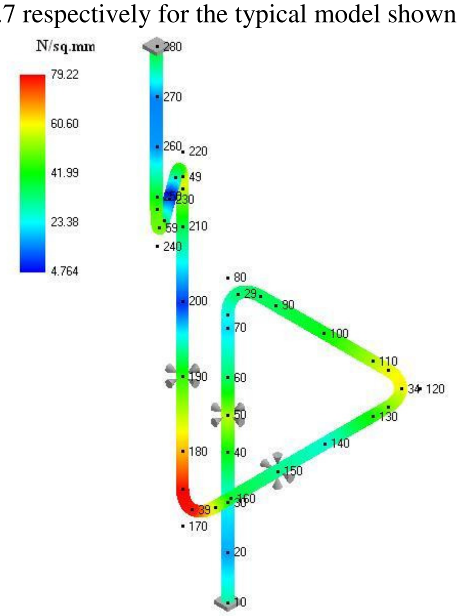

Fig. 4a: Thermal stresses in a typical pipeline

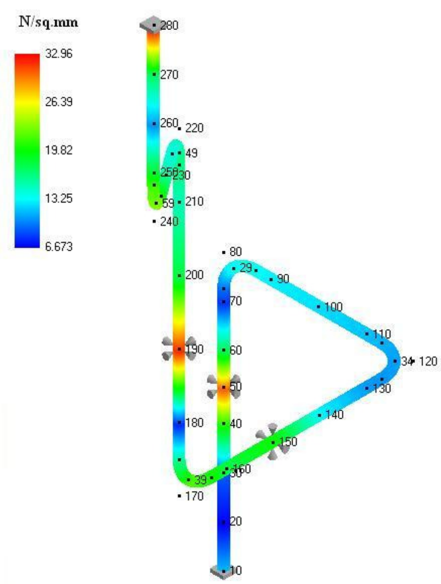

Fig. 4b: Sustained + inertial seismic stresses in a typical pipeline

CONCLUSION

All 499 pipelines analyzed for stresses have been found to conform to the code requirements. These pipelines have been selected based on the well defined selection criteria so as to represent the entire family of 6000 pipelines inside the process cells. Thus, the process cell piping of nuclear facility at Kalpakkam which have been classified as Class 2 nuclear safety related components qualifies as per ASME BPV Code, Section III, Division 1, Sub section NC. Also, the pipe supports have been found to conform to ASME BPV Code, Section III, Division 1, Sub section NF.

The selection criteria has saved lot of design time and design cost without compromising on safety aspects.

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