**APPENDIX 3A**


**REACTOR COOLANT SYSTEM ANALYSIS**

# APPENDIX 3A – REACTOR COOLANT SYSTEM ANALYSIS

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## APPENDIX 3A – REACTOR COOLANT SYSTEM ANALYSIS

3A      Reactor Coolant System Analysis

3A.1      Introduction

This appendix describes the methods that are used to analyze the reactor coolant system (RCS).

The RCS has two loops that are connected to the reactor vessel (RV). Each loop consists of one steam generator (SG), two reactor coolant pumps (RCPs), one hot leg pipe connecting RV and SG, and two cold leg pipes connecting SG, RCP, and RV. One pressurizer (PZR) is connected to one of the hot leg pipes. All components are located inside the containment building. The arrangement of the RCS is shown in Figures 5.1.3-1 and 5.1.3-2.

The RCS structural analyses for a safe shutdown earthquake (SSE) and in-containment refueling water storage tank (IRWST) discharge events are performed using the coupled model of the RCS, PZR, and containment building. The structural analyses for normal operating conditions and branch line pipe breaks (BLPBs) are performed by using separate RCS and the PZR models with the building stiffnesses at the support interfaces.

Dynamic analyses of the RCS and PZR under SSE, BLPB, and IRWST discharge conditions are performed by using time history analysis methods. A time history analysis adapts direct integration, mode superposition, and complex frequency response methods.

The results of the static and dynamic analyses are used for the design and analysis of the RCS components and their substructures. The major components of the RCS are designed in accordance with ASME Section III. Reasonable assurance of the structural integrity is provided by meeting the stress and fatigue limits in ASME Section III.

3A.2      Reactor Coolant System Structural Model

This section describes the structural analysis models of the RCS and PZR. The models are created using the finite element analysis code ANSYS, which is described in Subsection 3.9.1.2.1.7.

The two-loop RCS structural model, a lumped-mass stick (or beam) model, consists of the representations of the RCS components, RCS supports, reactor coolant loop (RCL) piping, and building structure. The component models consist of one RV with its internals, including the fuel and the supports; two SGs with their internals and supports; and four RCPs with motors and supports. All branch pipelines are eliminated from the RCS model because the mass and rigidity of the piping do not significantly influence the dynamic behavior of the RCS. This dynamic decoupling is in accordance with the decoupling criteria for the seismic analysis specified in NUREG-0800, SRP 3.7.2 and 3.7.3.

The RCS structure is mathematically represented by the elements in the ANSYS library listed below. The model is developed using the nominal dimensions and locations. The RCS and PZR models are illustrated in Figures 3A-1 and 3A-2, respectively. The spatial locations and orientations are defined by the set of orthogonal axes in which the y axis represents the vertical direction, and the x and z axes are in the horizontal plane.

The ANSYS library elements are as follows:

a. Beam element (3-dimensional)

b. Pipe element (3-dimensional straight pipe and elbow)

c. Spar element (3-dimensional)

d. Stiffness matrix element (3-dimensional)

e. Lumped mass (3-dimensional)

The beam element properties include the cross-sectional area, the moments of inertia about the x, y, and z axes of the element coordinate system, which is dependent on element orientation, and the shear areas. The beam element represents the portions with basic cross-sectional shapes such as a circle or rectangle. Typically, the RCS components and RV vertical support columns are represented by beam elements.

The straight pipe element properties are the inner and outer diameters, and elbow pipe element properties include the inner and outer diameters and the radius of curvature with

options for in-plane and out-of-plane bending flexibility factors. The pipe element represents primarily the RCL piping.

The spar element property is the cross-sectional area. The spar element represents primarily the supports pinned at both ends such as RCP support columns and the SG and RCP snubbers.

The stiffness matrix element represents the portions with complicated features that are not simply represented by beam or pipe elements. The stiffnesses of the RV primary inlet and outlet nozzles, and key attachments to components, are determined from static analyses using detailed finite element models, and the stiffness is modeled using the matrix element.

The mass of each component and its enclosed fluid is distributed where the dynamic characteristics can be represented and where the dynamic characteristic of the components can be adequately transmitted to other components by considering possible dynamic interactions between the components. The lumped masses are distributed on the locations that can maintain the center of gravity and the mass moment of inertia of the components.

The PZR is modeled in the same way the RCS model is generated and with the same element types and mass discretization.

To account for dynamic interactions between the RV and the integrated head assembly (IHA) including the control element driving mechanisms (CEDMs), the IHA reduced model is coupled to the RV model. The IHA reduced model is generated in the same way the RCS model is generated.

3A.2.1    RCS component supports

a.   Reactor supports

The RV is supported by four vertical columns located under the vessel inlet nozzles. A pad of the column is placed in the horizontal direction to allow radial growth of the vessel during thermal expansion. Four vertical columns also support the RV in the vertical direction. The supports are designed to accommodate normal, seismic, IRWST discharge, and BLPB loads. The column base plate acts

as a keyway to restrain the bottom of the RV for dynamic load conditions.  Typical RV supports are shown in Figure 3.8-12.

b.   Steam generator supports

The SG is supported at the bottom by a sliding base bolted to an integrally attached conical skirt.  The sliding base rests on low friction spherical head bearings, which allow unrestrained thermal expansion of the RCS.  Two keyways in the sliding base mate with embedded keys to guide the movement of the SG during expansion and contraction of the RCS and also limit movement of the bottom of the SG during seismic, IRWST discharge, and BLPB events.

A system of keys and snubbers located on the steam drum guide the top of the SG during expansion and contraction of the RCS and provide support during seismic, IRWST discharge, and BLPB events.  Typical SG supports are shown in Figure 3.8-13.

c.   Reactor coolant pump supports

RCP supports consist of four vertical columns that support the vertical loads of the RCP, two horizontal snubbers, two upper horizontal columns, and two lower horizontal columns.  The vertical and horizontal columns provide support for the pumps during normal operation, seismic, IRWST discharge, and BLPB conditions.  Typical RCP supports are shown in Figure 3.8-14.

d.   Pressurizer supports

The pressurizer is supported by a cylindrical skirt, as shown in Figure 3.8-15.  This skirt is welded to the pressurizer and bolted to the support structure.  The skirt is designed to withstand dead weight and normal operating loads as well as the loads due to seismic, pressurizer pilot-operated safety relief valve (POSRV) actuation, IRWST discharge, and BLPB events.  Four keys welded to the upper shell of the pressurizer provide an additional restraint for seismic, pressurizer POSRV actuation, IRWST discharge, and BLPB events.

3A.3      Static Analysis

To determine the structural behaviors for operating conditions, static analyses are performed.  The RCS is statically analyzed for the deadweight, internal pressure, and thermal expansion.

For the static analyses, special considerations are given to the supports and the branch lines: the snubbers and gapped supports are released so as not to restrain the RCS and the PZR, and the reaction loads determined from the branch line analyses at the nozzles on the components and piping are imposed on the corresponding nozzles to account for the influences of the branch lines.

3A.4      Dynamic Analysis

The RCS is designed to withstand the combined effects of normal operating conditions together with the dynamic loads such as earthquakes, postulated pipe breaks, and IRWST discharge events.  Dynamic analyses for these three events are performed to determine the dynamic responses of the RCS and the PZR.  This section describes the dynamic analyses.

Dynamic analyses are performed using the time history method of dynamic response analysis.  For a time history analysis, the total response is obtained by algebraically summing the response parameters in the time domain.

If there are significant modes that have frequencies greater than the frequency at which the spectral acceleration returns to the zero period acceleration (ZPA), the responses associated with high frequency modes are accounted for by using the method given in NRC RG 1.92, Rev. 2.

The damping values used in the analysis of seismic Category I and II structures, systems and components are selected from Table 3.7-7.  The damping values given in Table 3.7-7 include those recommended in NRC RG 1.61, Rev. 1.

The results of dynamic analyses contain the forces and moments, maximum displacements, response spectra, and time history.  The results of the RCS dynamic analyses are used for the design and analysis of RCS components and substructures including connected branch

lines. The resultant response spectra are broadened by 15 percent to account for uncertainties in the structural frequencies.

3A.4.1    Seismic Analysis

The RCS seismic model is coupled with the finite element model of the containment internal structures, which is incorporated into the model of nuclear island structures, as described in Subsection 3.7.2.3.3. The RCS model consists of the RV, SG, RCP, RCL piping, PZR, and PZR surge line. The RCS and the PZR models are described in Section 3A.2 and shown in Figures 3.A-1 and 3.A-2, respectively.

As described in Subsection 3.7.2.4, the soil-structure interaction (SSI) analysis of seismic Category I structures is performed using the complex frequency response method. The model of nuclear island structures including the RCS is used in the SSI analysis. Earthquake input motion for the SSI analysis in the form of synthetic acceleration time histories is described in Subsection 3.7.1.1.2.

3A.4.2    Postulated Pipe Break Analysis

To determine the structural responses to the break effects of the pipelines to which the leak-before-break (LBB) concept is not applied, the structural analyses of the RCS and the PZR are performed for each break. For the analyses, time-dependent break effects are applied to the RCS and the PZR models, which are modified from the model described in Section 3A.2 to accommodate the various dynamic effects: the mass is distributed to more nodes, and the gaps in the support systems are modeled. With the geometric nonlinearities of the gaps, the analyses are performed using the nonlinear time history analysis method. The integration time step for the analyses is short enough to be able to consider the instantaneous dynamic effects of pipe breaks. Break effects of a specific break are applied to the structural analyses on a case-by-case basis.

Break effects are as follows:

a.  Jet impingement and thrust

The determination of pipe thrust and jet impingement loads for postulated pipe breaks are described in Subsection 3.6.2.3.2.1.

b.  Subcompartment pressurization

The differential pressurization across the component described in Subsection 6.2.1.2 is considered to be external forces on the components for the structural analyses of the RCS and PZR.  External forces resulting from the differential pressurization surrounding the component in a compartment are determined by multiplying the differential pressures in nodalized spaces by the pressurized areas of the components and a factor of 1.4, as described in Subsection 6.2.1.2.3.

c.  Blowdown loads

Blowdown loads for postulated pipe breaks are described in Subsection 3.9.2.5.2.
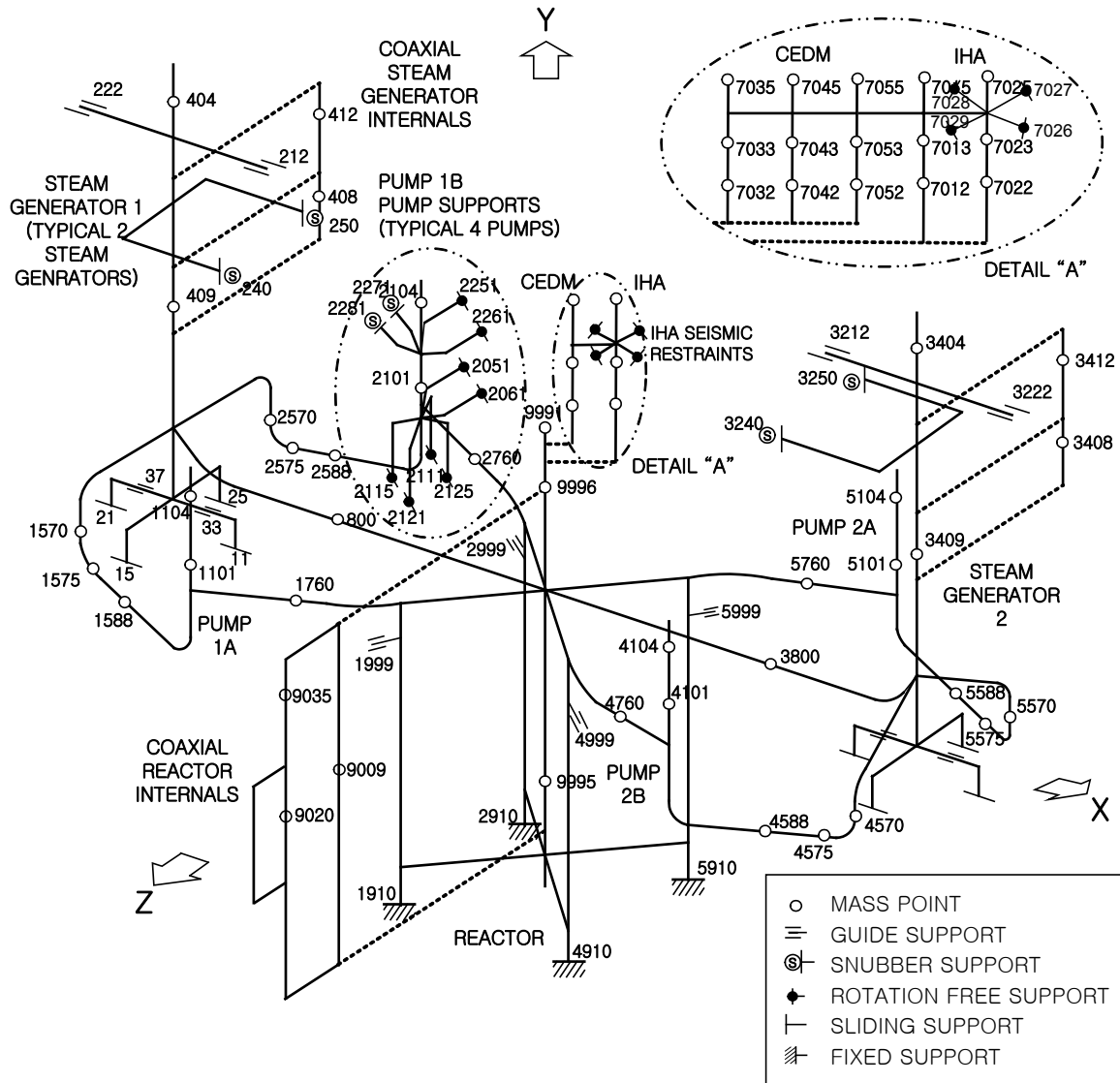
d.  Nozzle loads

Nozzle loads imposed by the dynamic motions of the pipe in an intermediate break and a nozzle break when more than two nozzles are connected to the same pipeline are considered for the structural analyses of the RCS and PZR.  The loads are determined from the analyses of the piping systems.

3A.4.3    In-containment Refueling Water Storage Tank Discharge Analysis

The hydrodynamic loads on the IRWST described in Subsection 6.8.4.3 are taken into consideration for the RCS and PZR structural analyses.

The IRWST discharge analysis model is a coupled model of the RCS and the containment internal structures.  Time history analyses are performed to determine structural responses to the hydrodynamic loads on the IRWST.

| COMPONENT NAME | MASS POINT NUMTER | DEGREES OF FREEDOM |
|---|---|---|
| REACTOR | 9996,9009,9020,9035,7012<br>7013,7015,7022,7023,7025<br>7032,7033,7035,7042,7043<br>7045,7052,7053,7055<br>9995,9991 | X,Y,Z<br>X,Y,Z<br>X,Y,Z<br>X,Y,Z<br>X,Z |
| STEAM GENERATOR | 404,412,3404,3412<br>408,409,3408,3409 | X,Y,Z<br>X,Z |
| RC PUMP | 1101,2101,4101,5101<br>1104,2104,4104,5104 | X,Y,Z<br>X,Y,Z |
| REACTOR COOLANT PIPING | 800,3800<br>1760,2760,4760,5760<br>1570,2570,4570,5570<br>1575,2575,4575,5575<br>1588,2588,4588,5588 | X,Y,Z<br>X,Y,Z<br>X,Y,Z<br>X,Y,Z<br>X,Y,Z |

| COMPONENT NAME | SUPPORT POINT NUMBER | RESTRATINT |
|---|---|---|
| REACTOR | 1999,2999,4999,5999<br>1910,2910,4910,5910<br>7026,7027,7028,7029 | FX,FZ<br>FIXED<br>FX,FY,FZ |
| STEAM GENERATOR | 11,15,21,25<br>3011,3015,3021,3025<br>33,37,3033,3037<br>240,3240,250,3250<br>212,222,3212,3222 | FY<br>FY<br>FZ<br>FX<br>FZ |
| REACTOR COOLANT PUMP (TYPICAL) | 2111,2115,2121,2125<br>2051,2061,2251,2261<br>2271,2281 | FY<br>FX,FZ<br>FX,FZ |

**Figure 3A-1  Reactor Coolant System Structural Analysis Model**

| | MASS POINT |
|---|---|
| ○ | MASS POINT |
| ≡ | GUIDE SUPPORT |
| ≢ | FIXED SUPPORT |

○ 6130

7300

7400 ≡ ≡ 7200

7500

○ 6120

| MASS POINT NUMBER | DEGREE OF FREEDOM |
|---|---|
| 6110, 6130 | X, Z |
| 6120 | X, Y, Z |

○ 6110

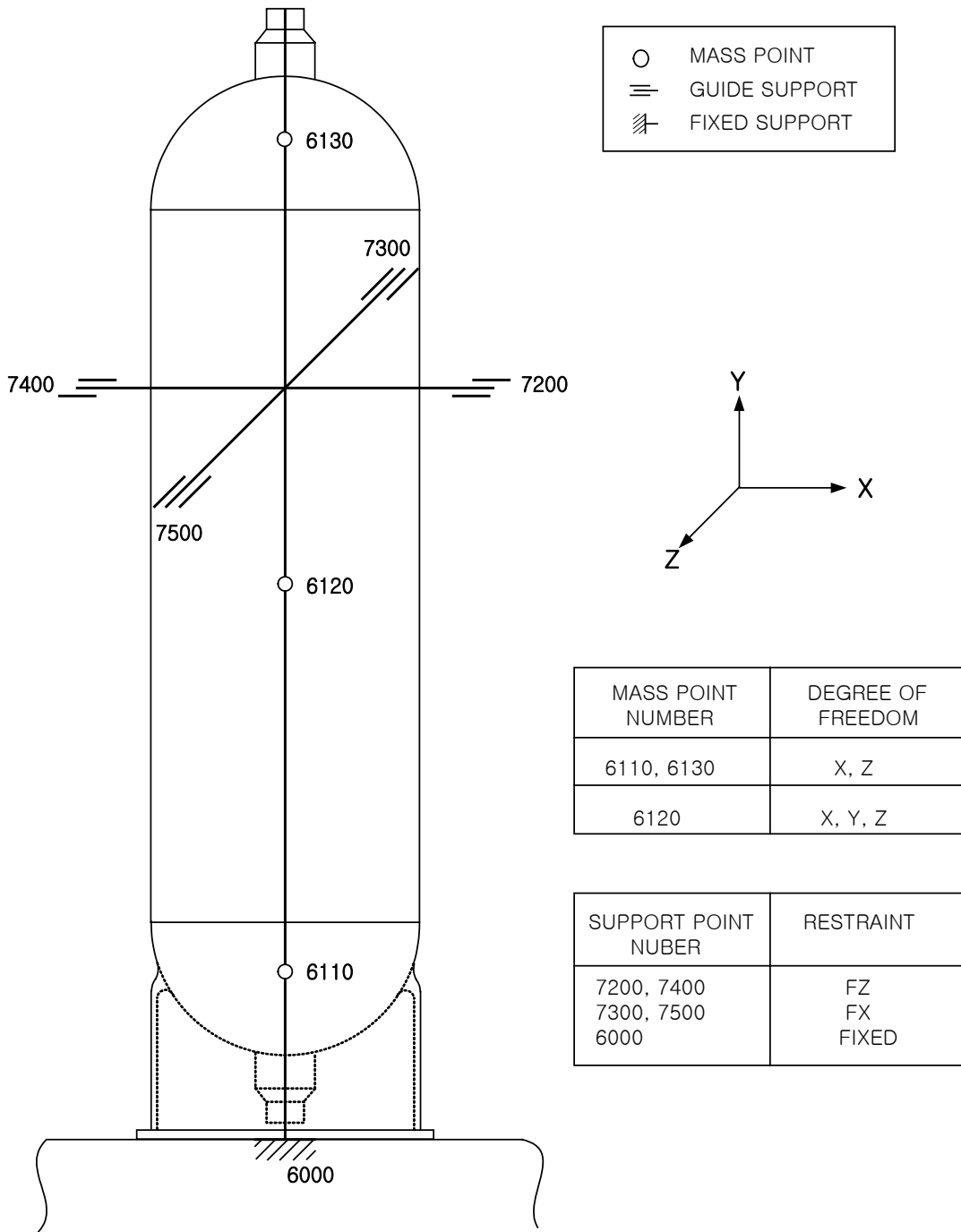| SUPPORT POINT NUBER | RESTRAINT |
|---|---|
| 7200, 7400 | FZ |
| 7300, 7500 | FX |
| 6000 | FIXED |

6000

**Figure 3A-2  Pressurizer Structural Analysis Model**