Summary of Stress Analysis Results for the US-APWR Main Steam Piping inside Containment Vessel

Non-Proprietary Version

March 2011

Revision History

Revision	Page	Description
0	All	Original Issue
1	ii	Changed title of Appendix 1-1 and Appendix 1-2.
	1-2	Charged Figure 1.0-1, 1.0-2 by having added branch piping.
	3-1	Changed results reflecting re-calculation.
	7-1	Revised revision number of document.
	8-2	Corrected description of design basis pipe break loads.
	8-3	Deleted description of DBPB displacement.
	9-5	Added Design Basis Pipe Break Analysis Method
	10-1	Changed version of program.
	11-1	Changed description of LBB evaluation.
	11-2	Changed results reflecting re-calculation.
	12-1	Revised revision number and corrected document title.
	A1-1-2	Changed description for clarification.
	A1-1-3	Changed Line spec No. and Fluid specific gravity.
	A1-1-4	Changed description for clarification. Added specification of branch piping.
	A1-1-5	Changed piping isometrics reflecting analysis model modification.
	A1-1-6	Corrected concentrated mass. Added mass of valves.

Revision History (Contd.)

1	A1-1-7	Changed support stiffness.
		Changed point number.
		Changed note about support point.
	A1-1-8	Changed Load No. from CA No. for clarification.
		Added the item of operating condition.
		Changed thermal displacement.
	A1-1-9 to A1-1-11	Changed Load No. from CA No. for clarification.
		Added the item of operating condition.
		Added data of Section II and Section III.
	A1-1-12	Changed Load No. from CA No. for clarification.
		Added the item of operating condition.
		Corrected data of Level C.
		Added data of Section II and Section III.
	A1-1-13 to A1-1-21	Changed Floor response curve.
		Separated CV penetration.
	A1-1-22 to A1-1-24	Changed seismic displacement.
		Change of equipment Nozzle or Building.
		Divided into X, Y and Z direction.
	A1-1-25 to A1-1-27	Added DBPB floor response curve.
	A1-1-28	Deleted DBPB displacement input data.
		Changed table number.
	A1-1-29	Changed steam temp, steam pressure and steam flow volume.
		Changed table number.
	A1-1-30	Changed analysis model.
	A1-1-31	Changed description of Steam hammer analysis model.
	A1-1-32, A1-1-33	Changed result of natural frequency analysis reflecting re-calculation.
	A1-1-34 to A1-1-36	Changed mode shape reflecting re-calculation.

Revision History (Contd.)

1	A1-1-37	Changed stress analysis results reflecting re-calculation. Deleted LBB evaluation results. LBB evaluation results see Appendix 2.
	A1-2-2	Changed description for clarification.
	A1-2-3	Changed Line spec No. and Fluid specific gravity.
	A1-2-4	Changed description for clarification. Added specification of branch piping.
	A1-2-5	Changed piping isometrics reflecting analysis model modification.
	A1-2-6	Corrected concentrated mass. Added mass of valves.
	A1-2-7	Changed support stiffness. Changed point number. Changed note about support point.
	A1-2-8	Changed Load No. from CA No. for clarification. Added the item of operating condition. Changed thermal displacement.
	A1-2-9 to A1-2-11	Changed Load No. from CA No. for clarification. Added the item of operating condition. Added data of Section II and Section III.
	A1-2-12	Changed Load No. from CA No. for clarification. Added the item of operating condition. Corrected data of Level C. Added data of Section II and Section III.
	A1-2-13 to A1-2-21	Changed Floor response curve. Separated CV penetration.
	A1-2-22 to A1-2-24	Changed seismic displacement. Change of equipment Nozzle or Building. Divided into X, Y and Z direction.

Revision History (Contd.)

1	A1-2-25 to A1-2-27	Added DBPB floor response curve.
	A1-2-28	Deleted DBPB displacement input data.
		Changed table number.
	A1-2-29	Changed steam temp, steam pressure and steam flow volume.
		Changed table number.
	A1-2-30	Changed analysis model.
	A1-2-31	Changed description of Steam hammer analysis model.
	A1-2-32	Changed result of natural frequency analysis reflecting re-calculation.
	A1-2-33 to A1-2-35	Changed mode shape reflecting re-calculation.
	A1-2-36	Changed stress analysis results reflecting re-calculation.
		Deleted LBB evaluation results.
		LBB evaluation results see Appendix 2.
	A2-2	Changed table of contents.
		Added LBB evaluation results.
	A2-3	Changed description for clarification.
		Changed item number.
	A2-4, A2-6, A2-7, A2-9	Changed item number.
	A2-10	Added LBB evaluation results.
	A2-11	Changed item number.
	A2-16 to A2-39	Added Seismic floor response curve.
	A2-40 to A2-45	Added Seismic anchor displacement input data.
	A2-16 to A2-39	Added LBB evaluation results for MS01 and MS02.

Revision History (Contd.)

2	ii	Changed page number.
	iii	Changed table number and page number.
	1-1	Changed sentence.
	1-2	Changed Figure 1.0-1 and Figure 1.0-2.
	2-1	Changed results reflecting re-calculation.
	5-1	Added description of valves.
	6-2	Added stress limit “S_h”.
	7-1	Revised revision number of document.
	8-2	Deleted description of fatigue.
		Changed description of Design Basis Pipe Break Loads.
	8-4 to 8-6	Deleted table 8.1-2.
		Changed table number.
	9-3	Changed figure 9.1-1.
	9-6	Added Design Basis Pipe Break Analysis Method.
	11-2	Changed results reflecting re-calculation.
	12-1	Revised revision number and corrected document title.
	A1-1-3	Changed schematic diagram for piping analysis.
		Added heat insulation weight.
	A1-1-4	Changed schematic diagram for piping analysis.
		Deleted description of *2.
	A1-1-5	Changed piping isometrics reflecting analysis model modification.
	A1-1-6	Corrected mass and name of valves.
		Changed mass of supports.
		Changed type of supports.
		Added mass of anchor.
	A1-1-7	Changed support stiffness.
		Changed point number.
		Changed note about support name.
		Added anchor.
		Changed local coordinate model.

Revision History (Contd.)

2	A1-1-9 to A1-1-12	Changed schematic diagram for thermal analysis.
	A1-1-22 to A1-1-24	Changed point number.
	A1-1-28	Changed point number.
	A1-1-30	Changed analysis model.
	A1-1-32, A1-1-33	Changed result of eigenvalue analysis reflecting re-calculation.
	A1-1-34 to A1-1-36	Changed mode shape reflecting re-calculation.
	A1-1-37	Changed stress analysis results reflecting re-calculation.
	A1-2-3	Changed schematic diagram for piping analysis. Added heat insulation weight.
	A1-2-4	Changed schematic diagram for piping analysis. Deleted description of *2.
	A1-2-5	Changed piping isometrics reflecting analysis model modification.
	A1-2-6	Corrected mass of valves and supports. Changed mass of supports. Changed type of supports. Added mass of anchor.
	A1-2-7	Changed support stiffness. Changed point number. Changed note about support name. Added anchor. Changed local coordinate model.
	A1-2-9 to A1-2-12	Changed schematic diagram for thermal analysis.
	A1-2-22 to A1-2-24	Deleted point number.
	A1-2-28	Changed point number.
	A1-2-30	Changed analysis model.

Revision History (Contd.)

2	A1-2-32	Changed result of eigenvalue analysis reflecting re-calculation.
	A1-2-33 to A1-2-35	Changed mode shape reflecting re-calculation.
	A1-2-36	Changed stress analysis results reflecting re-calculation.
	A2-11	Corrected wall thickness.
	A2-40 to A2-45	Changed point number. Deleted point number.
	A2-46 to A2-49	Changed LBB evaluation results reflecting re-calculation.

This document has been prepared by Mitsubishi Heavy Industries, Ltd. (“MHI”) in connection with the U.S. Nuclear Regulatory Commission’s (“NRC”) licensing review of MHI’s US-APWR nuclear power plant design. No right to disclose, use or copy any of the information in this document, other that by the NRC and its contractors in support of the licensing review of the US-APWR, is authorized without the express written permission of MHI.

This document contains technology information and intellectual property relating to the US-APWR and it is delivered to the NRC on the express condition that it not be disclosed, copied or reproduced in whole or in part, or used for the benefit of anyone other than MHI without the express written permission of MHI, except as set forth in the previous paragraph.

This document is protected by the laws of Japan, U.S. copyright law, international treaties and conventions, and the applicable laws of any country where it is being used.

MITSUBISHI HEAVY INDUSTRIES, LTD.
16-5, Konan 2-chome, Minato-ku
Tokyo 108-8215 Japan

Abstract

This report provides a summary of the stress analyses results of Main Steam Piping inside Containment Vessel in accordance with MHI’s commitment letter (Reference 9) concerning the content of the Technical Report.

From the results summarized in this report and a review of the component design drawings, it is concluded that the US-APWR Main Steam Piping inside Containment Vessel satisfies all of the requirements of the Design Specification (Reference 1) for structural integrity, operability, and safety.

Table of Contents

LIST OF TABLES III

LIST OF FIGURES IV

LIST OF ACRONYMS V

1.0 INTRODUCTION 1-1

2.0 SUMMARY OF RESULTS 2-1

3.0 CONCLUSIONS 3-1

4.0 NOMENCLATURE 4-1

5.0 ASSUMPTIONS AND OPEN ITEMS 5-1

5.1 ASSUMPTIONS 5-1

5.2 OPEN ITEMS 5-1

6.0 ACCEPTANCE CRITERIA 6-1

7.0 DESIGN INPUT 7-1

8.0 LOAD AND LOAD COMBINATIONS 8-1

8.1 LOADINGS 8-1

8.1.1 Design Temperature and Design Pressure 8-1

8.1.2 Sustained Loads 8-1

8.1.3 Thermal Expansion Loads 8-1

8.1.4 Earthquake Loads 8-2

8.1.5 Fluid Transient Loads 8-2

8.1.6 Design Basis Pipe Break Loads 8-2

8.1.7 Design Transients 8-3

8.2 LOAD COMBINATIONS 8-7

9.1 LOGIC DIAGRAM OF EVALUATION 9-1

9.2 STRUCTURAL ANALYSIS 9-3

9.2.1 Analysis model 9-3

9.2.2 Seismic Analysis Method 9-4

9.2.3 Time-History Method 9-5

9.2.4 Design Basis Pipe Break Analysis Method 9-6

9.3 STRESS EVALUATION 9-7

10.0 COMPUTER PROGRAMS USED 10-1

11.0 ANALYSIS RESULTS 11-1

12.0 REFERENCES 12-1

APPENDICES

Appendix 1-1 MS01 Main Steam A Line Piping Analysis Results A1-1-1

Appendix 1-2 MS02 Main Steam B Line Piping Analysis Results A1-2-1

Appendix 2 Leak Before Break Evaluation A2-1

List of Tables

Table 2-1	Summary of Most Limiting Results	2-1
Table 4-1	Symbol and Definition	4-1
Table 6-1	Main Steam Piping Stress Limits (greater than 1 inch piping)	6-2
Table 8.1-1	Design Temperature and Design Pressure	8-1
Table 8.1-2	Main Steam line design transients	8-4
Table 8.2-1	Loadings to be considered for various Load Condition	8-7
Table 10-1	Computer Program Description	10-1
Table 11-1	Main Steam Piping Result Summary	11-2

List of Figures

Figure 1.0-1 MS01 : Main Steam A line 1-2
Figure 1.0-2 MS02 : Main Steam B line 1-2
Figure 9.1-1 Evaluation Logic Diagram 9-2

List of Acronyms

The following list defines the acronyms used in this document.

SG	Steam Generator
RCL	Reactor Coolant Loop
RCP	Reactor Coolant Pump
BAC	Bounding Analysis Curve
SRSS	Square Root Sum of the Squares
MCP	Main Coolant Pipe
FRS	Floor Response Spectrum
IC	Inner Concrete
CV	Containment Vessel
FW	Feedwater
MS	Main Steam
LBB	Leak-Before-Break
DBPB	Design Basis Pipe Break
ECCS	Emergency Core Cooling System
MTCV	Main Turbine Control Valves
PCCV	Pre-Stressed Containment Vessel
NPS	Nominal Pipe Size
N/A	Not Applicable

1.0 INTRODUCTION

This Stress Analysis Technical Report is a non-certified version of the ASME Design Report for the US-APWR Main Steam Piping that has been prepared in support of the US-APWR DCD Review process. The content of this report follows the ASME guidelines for Design Reports (Section III Division 1 Appendix C) (Reference 5).

This Technical Report meets the requirements of the ASME Code Section III Division 1 NCA-3551.1 (Reference 5) by providing a summary of results and conclusions based upon detailed analyses that demonstrate the validity of the Main Steam Piping component to meet the requirements of the Design Specification (Reference 1).

For the design of Main Steam piping (i.e. NC-3600), the 1992 Edition of ASME Section III was used as required by 10CFR50.55a (b) (1) (iii).

The scope of this Technical Report includes the piping systems and components (PSC) of the following Main Steam Piping whose jurisdictional limits are identified in Figures 1.0-1 through 1.0-2. This includes the portions of the Main Steam System that are inside the PCCV. The selection of the Main Steam Piping is consistent with MHI's updated PSC design completion plan (Reference 9). MS lines A and D, as well as MS lines B and C, are identical in symmetric way. Therefore, Main Steam analyzed lines were selected as follows:

- MS01 and MS02 Main Steam A and B Lines

The Scope of the Report provides the following:

- A Summary of the Specification
- The Loads and Load Combinations
- The structural model of the piping including supports and penetrations.
- The results of the piping analysis in accordance with the piping Design Specification (Reference 1).
- A review of the calculated displacements and stresses including effects of stress intensification, demonstration of ASME III acceptability, and LBB applicability checks.

Nominal Size (inch)	
321	NPS 32 × 1.5 t
11	NPS 1 × Sch 80
12	NPS 1 × Sch 40
341	NPS 3/4 × Sch 80

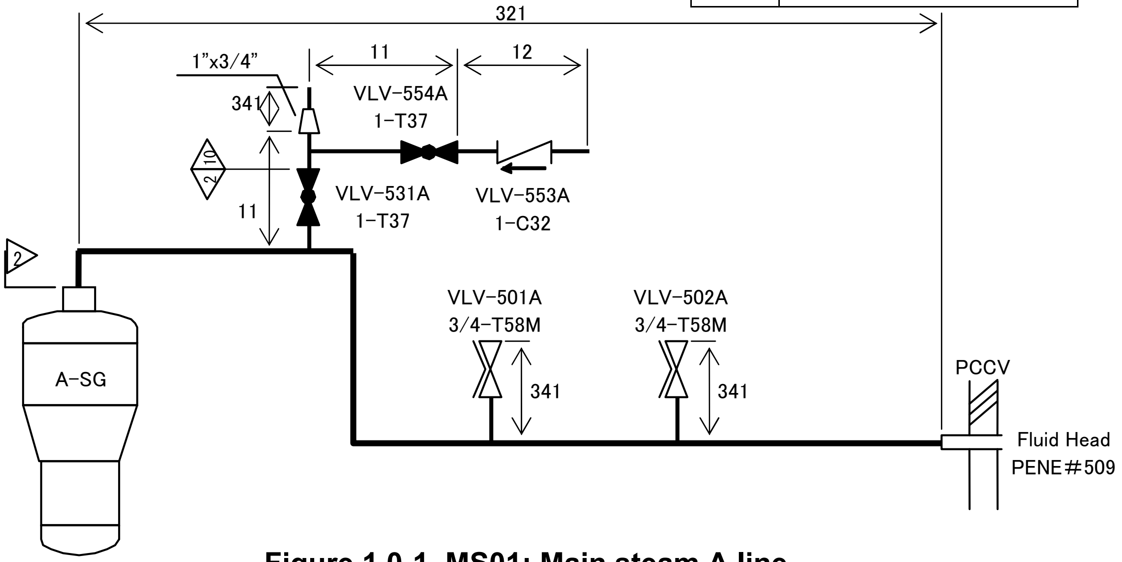


Figure 1.0-1 MS01: Main steam A line

Nominal Size (inch)	
321	NPS 32 × 1.5 t
11	NPS 1 × Sch 80
12	NPS 1 × Sch 40
341	NPS 3/4 × Sch 80

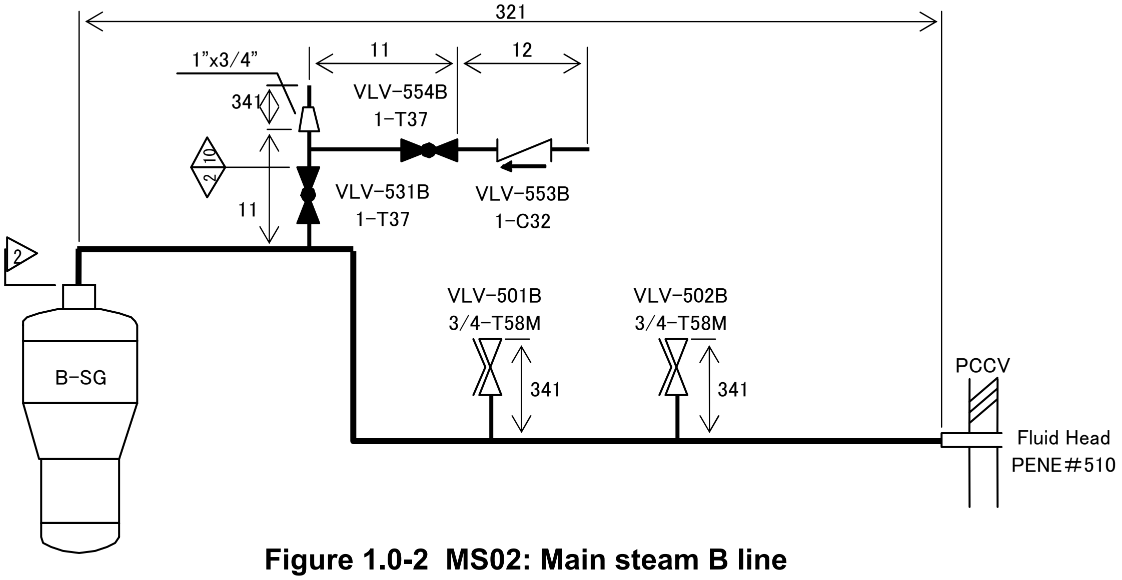


Figure 1.0-2 MS02: Main steam B line

2.0 SUMMARY OF RESULTS

The structural analysis results for each Main Steam Piping are summarized in Section 11 and Appendix-1, 2. The most limiting results in each evaluation are listed in Table 2-1 below.

Table 2-1 Summary of Most Limiting Results

Evaluated Part	Max Stress / Allowable Ratio	LBB Evaluation
MS01 Main Steam A Line		
MS02 Main Steam B Line		

3.0 CONCLUSIONS

The US-APWR Main Steam Piping inside Containment Vessel was designed to the requirements of the ASME Boiler and Pressure Vessel Code, Section III, 1992 Edition including the 1992 Addenda for Class 2 piping in accordance with the requirements of NC-3600, Service Loadings, Operating Conditions, and Test Conditions as specified in the Design Specification (Reference 1).

From the results summarized in this report, it is concluded that the US-APWR Main Steam Piping inside Containment Vessel satisfy all of the requirements of the Design Specification (Reference 1) for structural integrity, operability, and safety, and it is confirmed that applicable sections of the Main Steam Piping inside Containment Vessel satisfy the LBB criteria using Bounding Analysis Curves (BACs) as described in Appendix 2.

4.0 NOMENCLATURE

Table 4-1 Symbol and Definition

Symbol	Unit	Definition
S_y	psi	Yield Stress
S_c	psi	Allowable Stress at minimum (cold) temperature
S_h	psi	Allowable Stress at maximum (hot) temperature
S_A	psi	Allowable Stress Range for Expansion Stress
DL	-	Dead Load (The dead weight consists of the weight of the piping, insulation, and other loads permanently imposed upon the piping)
P	-	Design Pressure
P_M	-	Maximum Service Pressure
TH_{MTL}	-	ASME Service Level A (Normal) and Service Level B (Upset) Miscellaneous Thermal Loads
L_{DFN}	-	ASME Service Level A (Normal) Dynamic Fluid Loads associated with hydraulic transients such as relief/safety valve open or water/steam hammer
L_{DFU}	-	ASME Service Level B (Upset) Dynamic Fluid Loads associated with hydraulic transients such as relief/safety valve open or water/steam hammer
L_{DFE}	-	ASME Service Level C (Emergency) Dynamic Fluid Loads associated with hydraulic transients such as relief/safety valve open or water/steam hammer
L_{DFF}	-	ASME Service Level D (Faulted) Dynamic Fluid Loads associated with hydraulic transients such as relief/safety valve open or water/steam hammer
SSEI	-	Safe-Shutdown Earthquake Inertia Loads
SSEA	-	Safe-Shutdown Earthquake Anchor Loads
BS	-	Building Settlement
DBPB	-	Design Basis Pipe Breaks, include LOCA and non-LOCA
LOCA	-	Loss-of-Coolant Accident

5.0 ASSUMPTIONS AND OPEN ITEMS

5.1 Assumptions

The basic modeling assumptions from the detailed analyses are as follows:

1. Because the rigidity of supports has not been set by the procurer, the value was set on the basis of a trial design that was consistent with the earlier APWR plant.
2. Because the valve weight and rigidity have not been set by the valve specifications or the procurer, data was used for a similar valve of the earlier PWR plant.

5.2 Open Items

There are no open items in this Technical Report.

6.0 ACCEPTANCE CRITERIA

The stress limits acceptance criteria for Main Steam piping is specified in NC-3650 of ASME Section III. Table 6-1 lists the stress limits for Main Steam piping.

Table 6-1 Main Steam Piping Stress Limits

Condition	Service Level	Loading	Equation (NC-3650)	Stress Limit(3)
Design	-	P, DL	Eq. 8 NC-3652	1.5 S_h
Normal /Upset	A/B	P_M, DL, L_{DFN}, L_{DFU},	Eq. 9 NC-3653.1	Min(1.8 S_h, 1.5 S_y)
		TH_{MTL}	Eq. 10 NC-3653.2(a)	(1) S_A
		BS	Eq. 10a NC-3653.2(b)	3S_c
		P_M, DL, TH_{MTL}	Eq. 11 NC-3652.2(c)	(1) S_h +S_A
Emergency	C	P_M, DL, L_{DFE},	Eq. 9 NC-3654	Min(2.25 S_h,1.8 S_y)
Faulted	D	P_M, DL, L_{DFF}, $SSEI$, $DBPB$	Eq. 9 NC-3655	Min(3 S_h, 2 S_y)
		$SSEA$	(5)	(5) 6S_h, S_h

Notes:

1. Stresses must meet the requirements of either Equation 10 or 11, not both.
2. If, during operation, the system normally carries a medium other than water (air, gas, steam), sustained loads should be checked for weight loads during hydrostatic testing as well as normal operation weight loads.
3. ASME Boiler and Pressure Vessel Code, Section III(Reference 6)
4. Dynamic loads are combined by the SRSS method.
5. $$\frac{C_2 D_o M_{AM}}{2I} \leq 6.0 S_h \text{ and } \frac{F_{AM}}{A_M} \leq S_h$$

where

D_o = Pipe Outer Diameter
I = Pipe Moment of Inertia
A_M = Area of cross-section of the pipe
M_{AM} = Range of resultant moment due to *SSEA*
F_{AM} = Amplitude of longitudinal force due to *SSEA*
S_h = Allowable stress value

The use of 6S_h limit assumes elastic behavior of the entire piping system. In the case of unbalanced systems, the design is modified to eliminate unbalance or the piping is qualified by using an allowable limit of 3S_h.

7.0 DESIGN INPUT

The piping was designed based on the design inputs described in the Design Specification (Reference 1) and the documents listed as follows:

1. N0-CF00004 Revision 3 “Piping Design Criteria” (Reference 2)
2. N0-GB00005 Revision 5 ”Input Package of Stress Analysis of RCL Branch Piping and Main Steam Piping” (Reference 3)
3. N0-EE12001 Revision 4 ” Class 1 Equipment Design Transients” (Reference 4)

8.0 LOAD AND LOAD COMBINATIONS

8.1 Loadings

8.1.1 Design Temperature and Design Pressure

Main Steam Piping Design Temperature and Design Pressure are as shown in Table 8.1-1.

Table 8.1-1 Design Temperature and Design Pressure

Design Temperature (°F)	Design Pressure (psi)
568	1185

8.1.2 Sustained Loads

The weight of the piping system, its contents, any insulation and in-line equipment, and any other sustained loads identified in the Design Specification (Reference 1) were considered in the piping analysis. The mass contributed by the support was included in the analysis when it was greater than 10% of the total mass of the adjacent pipe span.

8.1.3 Thermal Expansion Loads

The effect of linear thermal expansion range during various operating modes was considered along with thermal movements of terminal equipment nozzles, anchors, or restraints (thermal anchor movements) corresponding to the operating modes. The stress free temperature was taken as 70°F.

8.1.4 Earthquake Loads

The effects of inertial loads and anchor movements due to SSE are considered as Service Level D loads in the design of piping.

8.1.5 Fluid Transient Loads

The steam hammer load is set in motion by the MTCV rapid closing. This load is functions of valve closing, flow rate, flow area, and fluid properties.

8.1.6 Design Basis Pipe Break Loads

US-APWR has applied the leak-before-break (LBB) methodology. As a result, dynamic evaluations of main coolant piping (MCP) break, surge line break, accumulator line break and main steam line break at the inside CV were eliminated. The postulated pipe break events that were evaluated for the reactor coolant system branch piping are as follows.

- Hot Leg Branch Line break at the 10 inch Schedule 160 Residual Heat Removal (RHR)/ Safety Injection (SI) line nozzle
- Cold Leg Branch line break at the 8 inch Schedule 160 RHR return line nozzle
- Feedwater Line break at the SG FW nozzle
- Main Steam Line break at the outside CV

Main Steam Line must be protected against mechanical loads due to a LOCA or secondary side pipe rupture (MS line break and FW line break) as follows.

a. Main Steam Line must be protected against RCL Branch Line pipe rupture and Main Steam Line break at the outside CV if Pressurizer Surge Line is in the intact loop.

b. Main Steam Line must be protected against Feedwater Line pipe rupture and Main Steam Line break at the outside CV if Main Steam Line is in the intact loop.

8.1.7 Design Transients

The design transient conditions are presented in Table 8.1-3.

Table 8.1-2 Main Steam line design transients (1/3)

Level A

Mark	Transient		Occurrence	Reference		Remark
				Document	Fig. or Table	
I-a	Plant heat-up (50F/h)		120	Ref. 4	Fig. I-1	
I-b	Plant cooldown (100F/h)		120		Fig. I-2	Including the transient of Loss of offsite power with natural circulation cooldown (10 times) and Safe shutdown (1 time) .
I-c-1	Ramp load increase between 15% and 100% of full power (5% of full power per minute)		600		Fig. I-3	
I-c-2	Ramp load increase between 50% and 100% of full power (5% of full power per minute)		19, 200		Fig. I-4	
I-d-1	Ramp load decrease between 15% and 100% of full power (5% of full power per minute)		600		Fig. I-5	
I-d-2	Ramp load decrease between 50% and 100% of full power (5% of full power per minute)		19, 200		Fig. I-6	
I-e	Step load increase of 10% of full power		600		Fig. I-7	
I-f	Step load decrease of 10% of full power		600		Fig. I-8	
I-g	Large step load decrease with turbine bypass		60		Fig. I-9	
I-h	Steady-state fluctuation and load regulation	i) Steady-state fluctuation	1×10^6		—	P_p±50psi, T_S±3.1F
		ii) Load regulation	8×10^5		Table 4	
I-i	Main feedwater cycling		2, 100		Fig. I-10	
I-j	Refueling		60		Fig. I-11	Water is replaced in 10 minutes.
I-k	Ramp load increase between 0% and 15% of full power		600		Fig. I-12	
I-l	Ramp load decrease between 0% and 15% of full power		600		Fig. I-13	
I-o	Core lifetime extension		60		Fig. I-16	
I-p	Primary leakage test		120		Fig. I-17	
I-q	Turbine roll test		10		Fig, I-18	
I-s	Secondary leakage test		120		—	

Table 8.1-2 Main Steam line design transients (2/3)

Level B						
Mark	Transient		Occurrence	Reference		Remark
				Document	Fig. or Table	
II-a	Loss of load		60	Ref. 4	Fig. II-1	
II-b	Loss of offsite power		60		Fig. II-2	
II-c	Partial loss of reactor coolant flow		30		Fig. II-3	
II-d	Reactor trip from full power	i) With no inadvertent cooldown	60		Fig. II-4	
		ii) With cooldown and no safety injection	30		Fig. II-5	
		iii) With cooldown and safety injection	10		Fig. II-6	
II-e	Inadvertent RCS depressurization		30		Fig. II-7	
II-f	Control rod drop		30		Fig. II-8	
II-g	Inadvertent safeguards actuation		30		Fig. II-9	
II-h	Emergency feedwater cycling		700		Fig. II-10	
II-i	Cold over-pressure		30		Fig. II-11	
II-j	Excessive feedwater flow		—		—	Be covered with the transient of Reactor trip from full power ii)
II-k	Loss of offsite power with natural circulation cooldown		—		—	Be covered with the transient of Plant cooldown
II-l	Partial loss of emergency feedwater		30		—	Please use the figure of the transient of Loss of offsite power.
II-m	Safe shutdown		—		—	Be covered with the transient of Plant cooldown

Table 8.1-2 Main Steam line design transients (3/3)

Mark	Transient	Occurrence	Reference		Remark
			Document	Fig. or Table	
Level C					
III-a	Small loss of coolant accident	5	Ref. 4	Fig. III-1	
III-b	Small steam line break	5		Fig. III-2	
III-c	Complete loss of flow	5		Fig. III-3	
III-d	Small feedwater line break	5		Fig. III-4	
III-e	SG tube rupture	5		Fig. III-5	
Level D					
IV-a	Large loss of coolant accident	1	Ref. 4	Fig. IV-1	
IV-b	Large steam line break	1		Fig. IV-2	
IV-c	RCP locked rotor	1		Fig. IV-3	
IV-d	Control rod ejection	1		Fig. IV-4	
IV-e	Large feedwater line break	1		Fig. IV-5	
Test					
V-a	Primary-side hydrostatic test	10	Ref. 4	—	
V-b	Secondary-side hydrostatic test	10		—	

8.2 Load Combinations

The loading conditions consist of various combinations of pressure, thermal and external loads.

The loads combinations considered in the analysis are listed in the Table below.

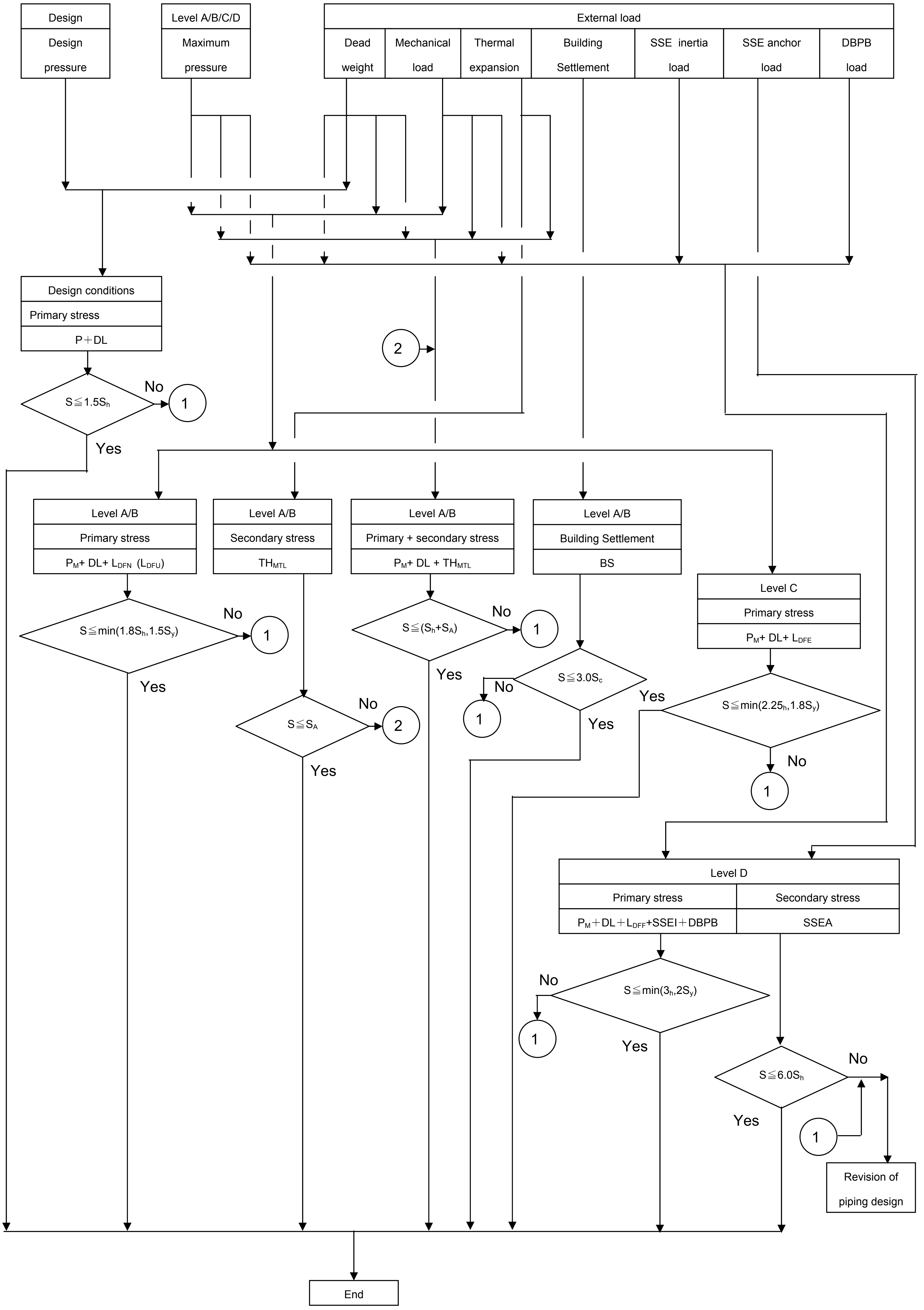
Table 8.2-1 Loadings to be considered for various Load Condition

Loading Conditions	Design	Level A/B	Level C	Level D
Design Pressure	✓			
Maximum Operating Pressure		✓	✓	✓
Dead Load	✓	✓	✓	✓
Mechanical load (steam hammer)		✓	✓	✓
Level A thermal, pressure transient load		✓		
Level B thermal, pressure transient load		✓		
Building Settlement (PCCV pre-stressed displacement load)		✓		
Level C pressure transient load			✓	
Level D pressure transient load				✓
SSE Loads				✓
Design Basis Pipe Break				✓

9.0 METHODOLOGY

9.1 Logic diagram of Evaluation

The evaluation logic diagram is shown in Figure 9.1-1.



Note 1: Either secondary stress evaluation or primary plus secondary stress evaluation may be used

Figure 9.1-1 Evaluation Logic Diagram

9.2 Structural Analysis

A structural analysis was performed with the following conditions according to the Piping Design Criteria (Reference 2).

9.2.1 Analysis model

For dynamic analysis, the piping system is idealized as a three dimensional space frame. The analysis model consists of a sequence of nodes connected by straight pipe elements and curved pipe elements with stiffness properties representing the piping, and other in-line components.

Piping restraints and supports are idealized as zero length springs with appropriate stiffness values for the restrained degrees of freedom.

In the dynamic mathematical model, the distributed mass of the system, including pipe, contents, and insulation weight, is represented as lumped masses located at each node, which is designated as a mass point.

The following formula is used to determine the spacing between two successive mass points. The PIPESTRESS program uses this formula for mass point spacing.

$$L = \sqrt{\left[\frac{K}{F_R}\right]\sqrt{\frac{EI}{W}}}$$

where

K = 0.743

L = Mass point spacing (ft)

F_R = Cut-off frequency (Hz)

E = Modulus of elasticity of pipe material (psi)

I = Moment of inertia of pipe cross-section (in^4)

W = Mass per unit length of piping + insulation + contents (lbm/ft)

Concentrated weights of in-line components, such as valves, flanges, and instrumentation, are also modeled as lumped masses.

Torsional effects of eccentric masses are included in the analysis.

9.2.2 Seismic Analysis Method

9.2.2.1 Damping Values

The damping value used for the SSE was 4%, which is consistent with Table 3 of the RG 1.61, Rev.1.

9.2.2.2 Combination of Modal Responses

For piping systems with no closely spaced modes, the SRSS method was applied to obtain the representative maximum response of each element, for each direction of excitation. A 10% grouping method was used for combining the responses of closely spaced modes.

9.2.2.3 High-Frequency Mode

The PIPESTRESS computer program was used for analyzing the piping systems. This program uses the LOF method to calculate the effect of the high frequency rigid modes. The results obtained were treated as an additional modal result from a non-closely spaced last mode, and were combined with other modal responses by the methods described in Subsection 9.2.2.2.

9.2.2.4 Directional Combination

The collinear responses due to each of the three spatial input components of motion are combined using the SRSS method

9.2.2.5 Seismic Anchor Motion

The effects of differential displacements of equipment or structures to which the piping system attaches during a SSE were considered.

The analysis of these seismic anchor motions (SAMs) was performed as a static analysis with all dynamic supports active. The results of this analysis were combined with the piping system seismic inertia analysis results by absolute summation.

Where supports were located within a single structure, the seismic motions were considered to be in-phase and the relative displacement between the support locations was considered in the analysis. Where supports were located within different structures, the seismic motions at these locations were assumed to move 180 degrees out-of-phase while performing the analysis.

9.2.2.6 Independent Support Motion Method

The supports were divided into support groups. Each support group was made up of supports that had similar time-history input. The responses caused by each support group were combined by the ABS method. The modal and directional responses were then combined as discussed above. Floor response spectrum curves used for ISM were generated using damping values identified in Section 9.2.2.1.

9.2.3 Time-History Method

The fluid transient analysis was performed to provide the hydraulic transient input for Main Steam structural analysis using RELAP5-3D(Reference7). The time history hydraulic forces were calculated using P2DLOP (see Section 10) from the pressure transient, flow rate, and other fluid property obtained by the fluid steam hammer analysis. The structural time history analysis was performed using PIPESTRESS (Reference 8) by modal superposition method.

9.2.4 Design Basis Pipe Break Analysis Method

Main Steam Line must be protected against mechanical loads due to the RCL branch line and secondary side pipe rupture as described in section 8.1.6. In these cases, Main Steam Line is vibrated by the anchor movements of the SG nozzle. Therefore, Main Steam Line response is calculated based on the response spectra of SG nozzle in these pipe rupture condition using ISM method. The supports were divided into two support groups. For one group, SG nozzle, response spectra was generated from time history of SG nozzle vibration. For another support group, other than SG nozzle, 0 amplitude acceleration was assumed. Static analyses were also performed to evaluate the effects of differential displacements of SG nozzle.

9.3 Stress Evaluation

Stress limits for design and service loadings are as follows.

(1) Design limit

(a) Primary stress evaluation (eq.8)

$$S_{SL} = B_1 \frac{PD_0}{2t_n} + B_2 \frac{M_A}{Z} \leq 1.5S_h$$

B_1, B_2: Stress indices
P: Design pressure
D_0: Outside diameter
t_n: Wall thickness
Z: Section modulus
M_A: Dead weight (no sustained mechanical load other than dead weight)

(2) Level A/B service limits

(a) Primary stress evaluation(eq.9)

$$S_{OL} = B_1 \frac{P_{\max} D_0}{2t_n} + B_2 (\frac{M_A + M_B}{Z}) \leq \min(1.8S_h, 1.5S_y)$$

P_{max}: Peak pressure
M_B: mechanical load (steam hammer load)

(b) secondary stress evaluation (eq.10)

$$S_E = \frac{iM_c}{Z} \leq S_A$$

$$S_A = f(1.25S_c + 0.25S_h)$$

i: Stress intensification factor
M_c: Thermal expansion

(c) primary plus secondary stress evaluation (eq.11)

$$S_{TE} = \frac{PD_0}{4t_n} + 0.75i(\frac{M_A}{Z}) + i(\frac{M_c}{Z}) \leq (S_h + S_A)$$

Evaluation may use either (b) or (c).

(d) Building Settlement evaluation (eq.10a)

$$\frac{iM_D}{Z} \leq 3.0S_c$$

M_D: Building Settlement load

(3) Level C service limit

(a) primary stress evaluation (eq.9)

$$S_{OL} = B_1 \frac{P_{\max} D_0}{2t_n} + B_2 \left(\frac{M_A + M_B}{Z}\right) \le \min(2.25S_h, 1.8S_y)$$

P_{max}: Peak pressure
M_B: Mechanical load (steam hammer load),

(4) Level D service limits

(a) Primary stress evaluation (eq.9)

$$S_{OL} = B_1 \frac{P_{\max} D_0}{2t_n} + B_2 \left(\frac{M_A + M_B}{Z}\right) \le \min(3S_h, 2S_y)$$

P_{max}: Peak pressure
M_B: Mechanical load (steam hammer load), SSE seismic inertia load, DBPB load
Note that the SSE seismic inertia load and DBPB load were combined by the SRSS method.

(b) Secondary stress evaluation

$$\frac{C_2 D_0 M_{AM}}{2I} \le 6.0S_h$$

$$\frac{F_{AM}}{A_M} \le S_h$$

M_{AM}: Range of resultant moment due to SSEA
F_{AM}: Amplitude of longitudinal force due to SSEA
A_M: Piping cross-sectional area

10.0 COMPUTER PROGRAMS USED

The Table below provides a brief description of each of the computer programs used.

Table 10-1 Computer Program Description

No.	Program Name	Version	Description
1	PIPESTRESS	3.6.2	PIPESTRESS is a computer program for the analysis of piping systems. This program is used for the analysis of ASME Code, Section Ⅲ, Class 1, 2, 3 and ASME B31.1 piping systems under various load conditions.
2	RELAP5-3D	2.4.2	RELAP5-3D is a computer program for the fluid transient analysis. This program is used for the analysis of a behavior, such as water hammer, by modeling flow volume and flow path.
3	P2DLOP	1.0	P2DLOP is an in-house program to obtain time history load for structural analysis by PIPESTRESS. This program uses the fluid transient analysis results generated by RELAP5-3D.
4	PICEP	06/30/87	PICEP is a program developed by the Electric Power Research Institute. This program is used for predicting leakage rate from assumed through-wall cracks in the leak-before-break evaluation of piping.

All these computer programs were verified and validated in compliance with the MHI quality assurance program. The computer programs were validated using one of the methods described below. Verification tests demonstrate the capability of the computer program to produce valid results for the test problems encompassing the range of permitted usage defined by the program documentation.

- Hand calculations
- Known solution for similar or standard problem
- Acceptable experimental test results
- Published analytical results
- Results from other similar verified programs

11.0 ANALYSIS RESULTS

The calculated stress-to–allowable ratio (calculated stress divided by allowable value) for the most limiting locations is summarized in the Table11-1. The ASME Code allowable limits were satisfied in all cases.

The detailed analysis models and results for each piping system are described in the Appendix 1.

LBB evaluation was applied and it was confirmed that Main Steam piping satisfies the LBB criteria using BAC as described in Appendix 2.

Table 11-1 Main Steam Piping Result Summary

Condition	Service Level	Loading	Equation (NC-3650)	Stress Limit	Stress-to-Allowable Ratio
Design	-	P, DL	Eq. 8 NC-3652	1.5 S_h	
Normal /Upset	A/B	P_M, DL, L_{DFN}, L_{DFU}	Eq. 9 NC-3653.1	Min(1.8 S_h, 1.5 S_y)	
		TH_{MTL}	Eq. 10 NC-3653.2(a)	S_A	
		BS	Eq. 10a NC-3653.2(b)	3S_c	
		P_M, DL, TH_{MTL}	Eq. 11 NC-3652.2(c)	S_h +S_A	
Emergency	C	P_M, DL, L_{DFE}	Eq. 9 NC-3654	Min(2.25 S_h,1.8 S_y)	
Faulted	D	P_M, DL, L_{DFF}, $SSEI$, $DBPB$	Eq. 9 NC-3655	Min(3 S_h, 2 S_y)	
		$SSEA$		6S_h	

12.0 REFERENCES

1. N0-GB00004 Revision 4 “Class 2 Main Steam Piping ASME Design Specification”
2. N0-CF00004 Revision 3 “Piping Design Criteria”
3. N0-GB00005 Revision 5 ”Input Package of Stress Analysis of RCL Branch Piping and Main Steam Piping”
4. N0-EE12001 Revision 4 ” Class 1 Equipment Design Transients”
5. ASME Boiler and Pressure Vessel Code, Section III,Division 1, 2001 Edition through 2003 Addenda
6. ASME Boiler and Pressure Vessel Code, Section III, Division 1, 1992 Edition
7. INEL,“RELAP5-3D Code manual”,2001
8. DST Computer Services. S.A.,“PIPESTRESS User’s Manual”,Version3.6.2
9. “Updated Design Completion Plan for US-APWR Piping Systems and Components” UAP-HF-10207, July, 2010.

Appendix 1-1

MS01
MSS Main Steam A Line

Piping Analysis Results

1. INPUT
1.1 Used for creating the pipe structural model
1.1.1 Block division and piping specifications Table A1-1-1-1
1.1.2 Piping isometrics Figure A1-1-1-1
1.1.3 Concentrated mass Table A1-1-1-2
1.1.4 Support point rigidity Table A1-1-1-3

1.2 Used for creating load conditions
1.2.1 Level A/B design transient see main text
1.2.2 Level A/B thermal displacement input data Table A1-1-1-4
1.2.3 Level A, B temperature and pressure input data Table A1-1-1-5
1.2.4 Level C, D maximum temperature and pressure input data Table A1-1-1-6
1.2.5 Seismic floor response curve Figure A1-1-1-2
1.2.6 Seismic anchor displacement input data Table A1-1-1-7
1.2.7 DBPB floor response curve Figure A1-1-1-3
1.2.8 PCCV prestress displacement input data Table A1-1-1-8
1.2.9 Initial condition and valve open characteristics (Steam hammer) Table A1-1-1-9

2. OUTPUT
2.1 PIPESTRESS analysis Model diagram Figure A1-1-2-1
2.2 Steam hammer analysis model diagram Figure A1-1-2-2
2.3 Natural frequency analysis results Table A1-1-2-1
2.4 Frequency mode diagram (primary to tertiary) Figure A1-1-2-3
2.5 Piping stress evaluation results Table A1-1-2-2

Table A1-1-1-1 Block division and piping specifications (1/2)

Table A1-1-1-1 Block division and piping specifications (2/2)

Table A1-1-1-2 Concentrated mass

Table A1-1-1-3 Support point rigidity

Table A1-1-1-4 Level A/B thermal displacement input data

(Point: 9010)

Table A1-1-1-5 Level A, B temperature and pressure input data (1/3)
(Section I)

Table A1-1-1-5 Level A, B temperature and pressure input data (2/3)

(Section II)

Table A1-1-1-5 Level A, B temperature and pressure input data (3/3)
(Section III)

Table A1-1-1-6 Level C, D maximum temperature and pressure input data

Figure A1-1-1-2 Seismic floor response curve (1/9)
Main Steam A Line (MS01) FRS for SG Nozzle
X(EW) direction (damping 4.0%)

Figure A1-1-1-2 Seismic floor response curve (2/9)
Main Steam A Line (MS01) FRS for SG Nozzle
Y(NS) direction (damping 4.0%)

Figure A1-1-1-2 Seismic floor response curve (3/9)
Main Steam A Line (MS01) FRS for SG Nozzle
Z(Vert) direction (damping 4.0%)

Figure A1-1-1-2 Seismic floor response curve (4/9)
Main Steam A Line (MS01) FRS for Piping Supports
X(EW) direction (damping 4.0%)

Figure A1-1-1-2 Seismic floor response curve (5/9)
Main Steam A Line (MS01) FRS for Piping Supports
Y(NS) direction (damping 4.0%)

Figure A1-1-1-2 Seismic floor response curve (6/9)
Main Steam A Line (MS01) FRS for Piping Supports
Z(Vert) direction (damping 4.0%)

Figure A1-1-1-2 Seismic floor response curve (7/9)
Main Steam A Line (MS01) FRS for CV Penetration
X(EW) direction (damping 4.0%)

Figure A1-1-1-2 Seismic floor response curve (8/9)
Main Steam A Line (MS01) FRS for CV Penetration
Y(NS) direction (damping 4.0%)

Figure A1-1-1-2 Seismic floor response curve (9/9)
Main Steam A Line (MS01) FRS for CV Penetration
Z(Vert) direction (damping 4.0%)

Table A1-1-1-7 Seismic anchor displacement input data (1/3)

Table A1-1-1-7 Seismic anchor displacement input data (2/3)

Table A1-1-1-7 Seismic anchor displacement input data (3/3)

Figure A1-1-1-3 DBPB floor response curve (1/3)
Main Steam A Line (MS01) DBPB FRS for SG Nozzle
X(EW) direction (damping 3.0%)

Figure A1-1-1-3 DBPB floor response curve (2/3)
Main Steam A Line (MS01) DBPB FRS for SG Nozzle
Y(NS) direction (damping 3.0%)

Figure A1-1-1-3 DBPB floor response curve (3/3)
Main Steam A Line (MS01) DBPB FRS for SG Nozzle
Z(UD) direction (damping 3.0%)

Table A1-1-1-8 PCCV prestress displacement input data

Table A1-1-1-9 Initial condition and valve open characteristics (Steam hammer) (1/2)

Table A1-1-1-9 Initial condition and valve open characteristics (Steam hammer) (2/2)

Figure A1-1-2-1 PIPESTRESS analysis model diagram

Figure A1-1-2-2 Analysis model for Main steam line steam hammer calculation

Table A1-1-2-1 Natural frequency analysis results

Figure A1-1-2-3 Frequency mode diagram (primary)

Figure A1-1-2-3 Frequency mode diagram (secondary)

Figure A1-1-2-3 Frequency mode diagram (tertiary)

Table A1-1-2-3 Piping stress evaluation results

(NC–3650 evaluation)

Appendix 1-2

MS02
MSS Main Steam B Line

Piping Analysis Results

1. INPUT

1.1 Used for creating the pipe structural model

1.1.1 Block division and piping specifications	Table A1-2-1-1
1.1.2 Piping isometrics	Figure A1-2-1-1
1.1.3 Concentrated mass	Table A1-2-1-2
1.1.4 Support point rigidity	Table A1-2-1-3

1.2 Used for creating load conditions

1.2.1 Level A/B design transient	see main text
1.2.2 Level A/B thermal displacement input data	Table A1-2-1-4
1.2.3 Level A, B temperature and pressure input data	Table A1-2-1-5
1.2.4 Level C, D maximum temperature and pressure input data	Table A1-2-1-6
1.2.5 Seismic floor response curve	Figure A1-2-1-2
1.2.6 Seismic anchor displacement input data	Table A1-2-1-7
1.2.7 DBPB floor response curve	Figure A1-2-1-3
1.2.8 PCCV prestress displacement input data	Table A1-2-1-8
1.2.9 Initial condition and valve open characteristics (Steam hammer)	Table A1-2-1-9

2. OUTPUT

2.1 PIPESTRESS analysis Model diagram	Figure A1-2-2-1
2.2 Steam hammer analysis model diagram	Figure A1-2-2-2
2.3 Natural frequency analysis results	Table A1-2-2-1
2.4 Frequency mode diagram (primary to tertiary)	Figure A1-2-2-3
2.5 Piping stress evaluation results	Table A1-2-2-2

Table A1-2-1-1 Block division and piping specifications (1/2)

Table A1-2-1-1 Block division and piping specifications (2/2)

Table A1-2-1-2 Concentrated mass

Table A1-2-1-3 Support point rigidity

Table A1-2-1-4 Level A/B thermal displacement input data

(Point: 9010)

Table A1-2-1-5 Level A, B temperature and pressure input data (1/3)
(Section I)

Table A1-2-1-5 Level A, B temperature and pressure input data (2/3)
(Section II)

Table A1-2-1-5 Level A, B temperature and pressure input data (3/3)
(Section III)

Table A1-2-1-6 Level C, D maximum temperature and pressure input data

Figure A1-2-1-2 Seismic floor response curve (1/9)
Main Steam B Line (MS02) FRS for SG Nozzle
X(EW) direction (damping 4.0%)

Figure A1-2-1-2 Seismic floor response curve (2/9)
Main Steam B Line (MS02) FRS for SG Nozzle
Y(NS) direction (damping 4.0%)

Figure A1-2-1-2 Seismic floor response curve (3/9)
Main Steam B Line (MS02) FRS for SG Nozzle
Z(Vert) direction (damping 4.0%)

Figure A1-2-1-2 Seismic floor response curve (4/9)
Main Steam B Line (MS02) FRS for Piping Supports
X(EW) direction (damping 4.0%)

Figure A1-2-1-2 Seismic floor response curve (5/9)
Main Steam B Line (MS02) FRS for Piping Supports
Y(NS) direction (damping 4.0%)

Figure A1-2-1-2 Seismic floor response curve (6/9)
Main Steam B Line (MS02) FRS for Piping Supports
Z(Vert) direction (damping 4.0%)

Figure A1-2-1-2 Seismic floor response curve (7/9)
Main Steam B Line (MS02) FRS for CV Penetration
X(EW) direction (damping 4.0%)

Figure A1-2-1-2 Seismic floor response curve (8/9)
Main Steam B Line (MS02) FRS for CV Penetration
Y(NS) direction (damping 4.0%)

Figure A1-2-1-2 Seismic floor response curve (9/9)
Main Steam B Line (MS02) FRS for CV Penetration
Z(Vert) direction (damping 4.0%)

Table A1-2-1-7 Seismic anchor displacement input data (1/3)

Table A1-2-1-7 Seismic anchor displacement input data (2/3)

Table A1-2-1-7 Seismic anchor displacement input data (3/3)

Figure A1-2-1-3 DBPB floor response curve (1/3)
Main Steam B Line (MS02) DBPB FRS for SG Nozzle
X(EW) direction (damping 3.0%)

Figure A1-2-1-3 DBPB floor response curve (2/3)
Main Steam B Line (MS02) DBPB FRS for SG Nozzle
Y(NS) direction (damping 3.0%)

Figure A1-2-1-3 DBPB floor response curve (3/3)
Main Steam B Line (MS02) DBPB FRS for SG Nozzle
Z(UD) direction (damping 3.0%)

Table A1-2-1-8 PCCV prestress displacement input data

Table A1-1-1-9 Initial condition and valve open characteristics (Steam hammer) (1/2)

Table A1-1-1-9 Initial condition and valve open characteristics (Steam hammer) (2/2)

Figure A1-2-2-1 PIPESTRESS analysis model diagram

Figure A1-2-2-2 Analysis model for Main steam line steam hammer calculation

Table A1-2-2-1 Natural frequency analysis results

Figure A1-2-2-3 Frequency mode diagram (primary)

Figure A1-2-2-3 Frequency mode diagram (secondary)

Figure A1-2-2-3 Frequency mode diagram (tertiary)

Table A1-2-2-3 Piping stress evaluation results

(NC–3650 evaluation)

Appendix 2

LEAK BEFORE BREAK EVALUATION

TABLE OF CONTENTS

A2 LEAK BEFORE BREAK EVALUATION A2-3
A2.1 INTRODUCTION A2-3
A2.2 LBB EVALUATION METHOD A2-3
  A2.2.1 BOUNDING ANALYSIS CURVE APPROACH A2-3
    A2.2.1.1 LEAK RATE DETERMINATION A2-3
    A2.2.1.2 FRACTURE MECHANICS ANALYSIS A2-4
    A2.2.1.3 GENERATION OF BAC A2-6
  A2.2.2 CALCULATION OF LBB EVALUATION POINTS A2-7
  A2.2.3 BAC FOR MAIN STEAM LINE LBB EVALUATION A2-9
A2.3 LBB EVALUATION RESULTS A2-10
A2.4 REFERENCES A2-11

A2 LEAK BEFORE BREAK EVALUATION

A2.1 Introduction

The leak-before-break (LBB) evaluation of the US-APWR follows the methodology in accordance with General Design Criteria (GDC) 4 of 10CFR50, Appendix A (Ref. 1), NUREG-0800, Standard Review Plan (SRP) 3.6.3, Rev. 1, (Ref. 2), and NUREG-1061, Volume 3 (Ref. 3). The evaluation includes an assessment of all potential failure mechanisms, and development of bounding analysis curves (BACs) that define the allowable maximum stress as a function of the normal operating stress for each piping systems or subsystems with different materials.

The LBB analysis is described in detail in Section 3.6.3 of the US-APWR Design Control Document (DCD), with details in Appendix 3B. That appendix provides the development of the BACs for the piping.

This appendix shows the LBB evaluation method and based on DCD and LBB evaluation results.

A2.2 LBB Evaluation Method

A2.2.1 Bounding analysis curve approach

Work has currently been completed to update the BAC analysis for Appendix 3B of the DCD, Rev.1. The following methods are used for the LBB evaluation:

(1) Calculation of a leakage rate and determination of leakage flaw sizes as a function of normal operating conditions over the range of expected normal operating condition stresses.

(2) Calculation of critical flaw sizes as a function of stress due to pressure and applied bending moments over the expected range of stress.

(3) Development of the BACs from the above that include the margin factors of 2 on crack size and 10 on leakage from SRP 3.6.3.

A2.2.1.1 Leak Rate Determination

The DCD described the thermal-hydraulics model used to develop the BAC curves. The fundamental equations for calculation of flow through a circumferential crack in a pipe are described. The revised leakage rate calculations have been made using the following modified approach:

(1) For convenience, the EPRI-developed PICEP computer program (Ref. 4) was used to calculate leakage. PICEP incorporates the thermal-hydraulic model described in the DCD, but has improved methods for calculation of the crack opening area including the EPRI-developed methods for elastic plastic fracture mechanics (Ref. 5).

(2) For conservatism, the crack opening area was calculated without taking credit for the plastic opening by setting the Ramberg-Osgood coefficient α equal to ~0. This is consistent with the approach in the DCD. In addition, the plastic zone correction factor was conservatively based on a flow stress (not yield stress) equal to 1.6 times the

Code minimum flow stress (average of Code minimum yield and tensile strength), allowing only a small amount of plastic zone correction that can affect the predicted crack opening area only when normal operating stresses are quite high.

(3) The coefficient of discharge (C_D) was taken as 0.61 which is the PICEP default. Consistent with testing conducted at the time of the PICEP development and verification that it would adequately calculate leakage, the crack roughness for assumed fatigue cracks was taken as 0.000197 inches and no turns were included (Ref. 6). These assumptions are consistent with those made at the time that SRP 3.6.3 and NUREG-1061 Volume 3 were published that required a factor of 10 between the calculated leakage and the plant leakage detection system detection capability to cover various uncertainties that might exist.

(4) Based on a review of revisions to Regulatory Guide 1.45 (Ref. 7), it was determined that the US-APWR leakage detection system can be reduced to 0.5 gpm, such that the leakage flaw sizes can be based on 5 gpm predicted leakage, maintaining the factor of 10 on leakage detection capability defined in SRP 3.6.3.

A2.2.1.2 Fracture Mechanics Analysis

The approach for fracture mechanics evaluation to determine critical flaw size is as described in the DCD. The elastic-plastic J-Integral-Tearing modulus (J-T) fracture mechanics methodology is used. In the evaluation, the stress-strain relationship of the base metal is used to calculate the applied J-integral. The limiting material J-T curve for both the base metal and the weld metal were used to establish the critical flaw size.

In performing the fracture mechanics analysis, the stress strain curve can be fit based on ASME Code minimum properties to determine Ramberg-Osgood material parameters using the approach:

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + \alpha\left[\frac{\sigma}{\sigma_0}\right]^{n}$$

Here σ and ε are the true stress and true strain, σ_o and ε_o are the reference stress and reference strain (that may be taken as yield stress and yield strain or any other consistent values) and α and n are the Ramberg-Osgood (R-O) parameters.

If a stress-strain curve at the temperature of interest were available, the R-O parameters could be obtained by curve fitting over the strain range of interest. In the absence of the actual stress-strain curve of the material, a methodology for determining the R-O parameters based on ASME Code minimum-specified mechanical properties is used (Ref. 8). The parameters were determined by using material 0.2 percent offset yield strength as σ_o and the following equations:

$$\alpha \approx \frac{0.002}{e_y}$$

$$n = \frac{\ell n\left[\frac{1}{\alpha}\left(\frac{\ell n(1+e_u)}{\ell n(1+e_y)}\right) - \frac{S_u(1+e_u)}{S_y(1+e_y)}\right]}{\ell n\left[\frac{S_u(1+e_u)}{S_y(1+e_y)}\right]}$$

where S_u and S_y represent Code minimum ultimate stress and yield stress respectively that can be obtained from Section II of the ASME Code (Ref. 9) as a function of temperature. The yield strain (e_y) is determined as:

$$e_y = \frac{S_y}{E}$$

where E (modulus of elasticity) can also be obtained from the ASME Code. The ultimate strain (e_u) is not specified as a function of temperatures in the ASME Code, hence the room temperature minimum elongation value from the ASME Section II properties for SA-333 Grade 6 is assumed for all temperatures. The methodology is not very sensitive to the choice of e_u when determining α and n by using the equations above.

The choice of the R-O parameters based on either yield strength or flow stress does not change the prediction of the plastic portion of the J-Integral using the EPRI/GE EPFM estimation equations (Ref. 5) since the stress strain curve is identical in either case. This is why a reference stress nomenclature is used. The elastic portion of the J-Integral is affected however, with lower values of reference stress increasing the computed elastic J-Integral since a plastic zone correction is made. In NUREG/CR-6540 (Ref. 10) and NUREG/CR-6235 (Ref. 11), it was stated that more recent work by Battelle had not used the plastic zone correction at all, since the effect of the plastic zone correction is inherently included in the plastic J-Integral calculation. Thus, it is acceptable to use the higher flow stress in determining the RO parameters as there is still some contribution due to the elastic J-integral. The Ramberg-Osgood parameters based on the flow stress (α_{flow}, ε_{flow}) may be determined from those above based on the yield stress (α_y, ε_y) by using the following equations:

R-O Coefficient: $\alpha_{flow} = \alpha_y (\sigma_{flow}/\sigma_y)^{n-1}$

R-O Exponent: $n_{flow} = n_{yield}$

Material of the main steam pipe is planned to be SA333 Gr.6. The specific material data to be used for the fracture mechanics evaluations, as specified in Standard Review Plan 3.6.3, are not yet available. Thus, ASME Code minimum properties based on the Code were used and shown in Table A2-2. An approach has been developed whereby the fracture properties for the base metal and welding will be specified to the piping supplier and fabricator to assure that the BAC provided herein will be met. This is a suitable alternate to testing of typical material that may or may not be similar to that procured.

As part of this evaluation, a set of material properties have been assumed that will provide sufficient margin in determination of the BAC, and that can be obtained in the procurement process. The required material property is the J-resistance (JR) curve ($J = C\Delta a^m$) for the base metal and the weld metal. The test procedure requires the following as a supplemental requirement for material procurement and welding qualification:

1. Testing shall be conducted to determine the JR curve. All testing shall be conducted at a test temperature between 535ºFand 550ºF to bound the main steam line temperature.
2. Using material tensile testing at the same temperature, the yield strength and ultimate tensile strength shall be determined. The flow stress shall be determined as the average of the yield and ultimate tensile strength. The ratios of the yield strength and flow stress to those based on minimum Code values at this temperature shall be determined. The minimum of the ratios so determined for the flow stress and the yield stress shall be denoted as the stress factor (SF).
3. The material C and m parameters to fit the JR curve shall be established.
4. Using the procedures as allowed in NUREG-1061 Volume 3, a required J-T curve shall be constructed based on $J = C_{SF}\ \Delta a^{0.6}$, where C_{FS} is determined from the equation in Figure A2-1 and the methods previously described herein. In constructing the JT curve, the Code values of modulus of elasticity shall be used, and flow stress shall be based on Code minimum yield and tensile strengths. The J-integral may be extrapolated to a value not exceeding twice the valid J-Integral limit as determined in the JR testing. A set of JT curves so determined as shown in Figure A2-2 for the range of expected stress factors between 1.0 and 1.6.
5. Based on the actual testing of the base material and weld materials, construct a J-T curve based on the actual C and m of the specific material test, performing the extrapolation to no more than twice the valid J-Integral for the test. Similar to above, the Tearing Modulus (T) shall be based on Code modulus of elasticity and minimum strength properties at the test temperature.

Provided that the J-T curve determined in item 5) above exceeds the required J-T curve of 4), then the material will satisfy the BAC requirements.

The required J-resistance curve relationship has been established based on use of ASME Code modulus of elasticity and minimum strength properties at 550ºF in the fracture mechanics analysis. Review of the curves against actual test data from the literature has been attempted, but valid test data for material representative of the main steam line and its thickness are very limited.

It has been established that higher stress factors (and the associated lower JT curves) are all essentially equivalent at the lower normal stress part of the BAC curve, and use of higher strength materials produce slightly higher BAC curves at higher stresses. Thus, use of Code minimum properties in establishing the BAC is conservative.

A2.2.1.3 Generation of BAC

The BAC methodology uses a LBB assessment diagram to show that LBB requirements are met for all weld locations in each piping system. In the BAC diagram $\sigma_{nor} = |P_m| + |P_b|$, the sum of the membrane stress and the bending stress under normal operation is plotted along the abscissa, and $\sigma_{max} = |P_{m\_max}| + |P_{b\_max}|$, the absolute sum of the membrane stress and the bending stress under the maximum load is plotted along the ordinate. The procedure used in developing the BAC diagram was as follows:

(1) Determine the leakage crack length for a crack with a leak rate 10 times as large as the detectable leak rate by applying abscissa's normal stress σ_{nor}.

(2) Based on a critical crack size of twice the leakage crack length, determine the maximum stress σ_{max} that is required to produce this critical crack size.

(3) Perform the above steps at a sufficient number of points of normal operating stress to develop of smooth curve of the maximum stress σ_{max} as a function of the abscissa's normal stress σ_{nor}.

(4) For the modified BACs, the normal operating stress was varied from that due to pressure up to a limit of 50 ksi. This upper bound is arbitrary and is a stress greater than will be limited by the ASME Code stress limits for the piping that also must be satisfied.

For the BAC curves, the membrane stresses are calculated based on the axial force divided by the metal area. For the piping evaluated in this report, the axial loads due to loads other than pressure were not significant. The axial pressure force was based on the internal pipe pressure times the internal area of the weld. For convenience, the bending stresses included in the BAC curves were based on the piping moment divided by the weld section modulus, effectively using the stress at the outside of the piping. All of the BACs are developed using the nominal thickness and diameter of the welds.

Using the models described above, a BAC curve for the main steam line has been developed and is shown in Figure A2-3.

A2.2.2 Calculation of LBB Evaluation Points

The assessment of LBB acceptability was performed based on the calculated stresses at each weld in the piping system being evaluated. For each weld, stresses for normal operation and the maximum stress conditions were calculated from the piping stress analysis. Per the requirements in SRP 3.6.3, the maximum stress was a combination of the effects of pressure + dead weight + thermal expansion + maximum seismic stress.

The stress for normal operation along the abscissa of the BAC was calculated for each weld in the piping system as follows.

1) Calculate the algebraic sum of the axial force, the bending and torque moment due to deadweight, the internal pressure, and the thermal expansion using the following equations:

$$F = F_{DW} + F_{Th} + F_P$$

$$M = \sqrt{\left((M_X)^2 + (M_Y)^2 + (M_Z)^2\right)}$$

$$M_X = (M_X)_{DW} + (M_X)_{Th}$$

$$M_Y = (M_Y)_{DW} + (M_Y)_{Th}$$

$$M_Z = (M_Z)_{DW} + (M_Z)_{Th}$$

Where F = Axial force

M = Bending moment

Subscripts indicate the loads shown below

DW = Deadweight

Th = Thermal expansion

P = Internal pressure

x, y and z = Component of x,y and z direction.

2) Calculate the cross sectional area A and the section modulus Z assuming the minimum wall thickness.

3) Calculate the stress σ_{nor} at the evaluation point under normal operation.

$$\sigma_{nor} = P_m + P_b = F/A + M/Z$$

The maximum stress for each weld in the piping system was evaluated as follows:

1) Calculate the absolute sum of the axial force, the bending and torque moment due to deadweight, the internal pressure, the thermal expansion, and earthquake using the following equations:

$$\begin{aligned}
|F| &= |F_{DW}| + |F_{Th}| + |F_P| + |F_{SSE}| + |F_{SAM}| \\
|M| &= \sqrt{\left((M_X)^2 + (M_Y)^2 + (M_Z)^2\right)} \\
M_X &= |(M_X)_{DW}| + |(M_X)_{Th}| + |(M_X)_{SSE}| + |(M_X)_{SAM}| \\
M_Y &= |(M_Y)_{DW}| + |(M_Y)_{Th}| + |(M_Y)_{SSE}| + |(M_Y)_{SAM}| \\
M_Z &= |(M_Z)_{DW}| + |(M_Z)_{Th}| + |(M_Z)_{SSE}| + |(M_Z)_{SAM}|
\end{aligned}$$

Where subscripts indicate the following loads.

SSE = Inertia load due to SSE

SAM = Seismic anchor motion load due to SSE.

2) Calculate stress under the maximum load σ_{max} at the weld joint.

$$|\sigma_{\max}| = |P_{m\_\max}| + |P_{b\_\max}| = \left(|F|/A + |M|/Z\right)$$

The BAC assessment points are then plotted on the BAC to determine LBB acceptance. In some cases, the actual stresses in the piping system, calculated using the methods above, fall in the regions below the BAC, then LBB requirements are satisfied.

A2.2.3 BAC for Main Steam Line LBB Evaluation

Table A2-1 lists the Main steam piping property selected for setting the BAC. The Main steam piping BAC is shown in Figure A2-3. Table A2-3 is the tabulated BAC points.

A2.3 LBB Evaluation Results

The BAC assessment points for Main steam piping are plotted for US-APWR Standard Plant (STD) condition and North Anna unit 3 Plant (NA3) condition separately based on the Main steam piping structural analysis results described in appendix A1. Here, in order to get more realistic structural analysis results to satisfy the LBB criteria, reanalyses were performed partially using detailed input data described in following Tables and Figures.

1. Seismic floor response curve of STD	Figure A2-4
2. Seismic floor response curve of NA3	Figure A2-5
3. Seismic anchor displacement input data of STD	Table A2-4
4. Seismic anchor displacement input data of NA3	Table A2-5

LBB evaluation results for Main steam piping are shown in following Figures.

1. LBB evaluation results for MS01 (STD)	Figure A2-6
2. LBB evaluation results for MS01 (NA3)	Figure A2-7
3. LBB evaluation results for MS02 (STD)	Figure A2-8
4. LBB evaluation results for MS02 (NA3)	Figure A2-9

NOTE

.

A2.4 References

1. ‘General Design Criteria for Nuclear Power Plants,’ “Domestic Licensing of Production and Utilization Facilities,” Energy. Title 10, Code of Federal Regulation, Part 50, Appendix A, U.S. Nuclear Regulatory Commission, Washington, D.C.

2. Leak-Before-Break Evaluation Procedures,’ “Design of Structures, Components, Equipment, and Systems,” Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants. NUREG-0800, Standard Review Plan 3.6.3, Rev. 1, U.S. Nuclear Regulatory Commission, Washington, DC, March 2007.

3. “Evaluation of Potential for Pipe Breaks,” Report of U.S. NRC Piping Review Committee. NUREG-1061, Vol. 3, U.S. Nuclear Regulatory Commission,” Washington, DC, 1984.

4. PICEP: Pipe Crack Evaluation Program. NP-3596-SR, Rev. 1, Electric Power Research Institute, 1987.

5. Kumar, V, and German, M. D., “Elastic-Plastic Fracture Analysis of Through-Wall and Surface Flaws in Cylinders,” EPRI NP-5596, January 1988.

6. D. Abdollahian and B. Chexal, “Calculation of Leak Rates Through Cracks in Pipes and Tubes,” EPRI NP-3395, Electric Power Research Institute, Palo Alto, CA, December 1983.

7. Regulatory Guide 1.45, “Guidance On Monitoring And Responding To Reactor Coolant System Leakage.” U. S. Nuclear Regulatory Commission, May 2008.

8. Cofie, N.G., Miessi, G.A., and Deardorff, A.F., “Stress-Strain Parameters in Elastic-Plastic Fracture Mechanics,” Transactions of the 10th International Conference on Structural Mechanics in Reactor Technology, Volume L – Inelastic Behavior of Metals and Constitutive Laws of Materials, August 14-18, 1989, Anaheim, Ca, USA, pp 91-96.

9. ASME Boiler and Pressure Vessel Code, Sections II 2001 Edition with 2003 Addenda.

10. NUREG/CR-6540, “State of the Art Report on Piping Fracture Mechanics” U. S. Nuclear Regulatory Commission, November 1997

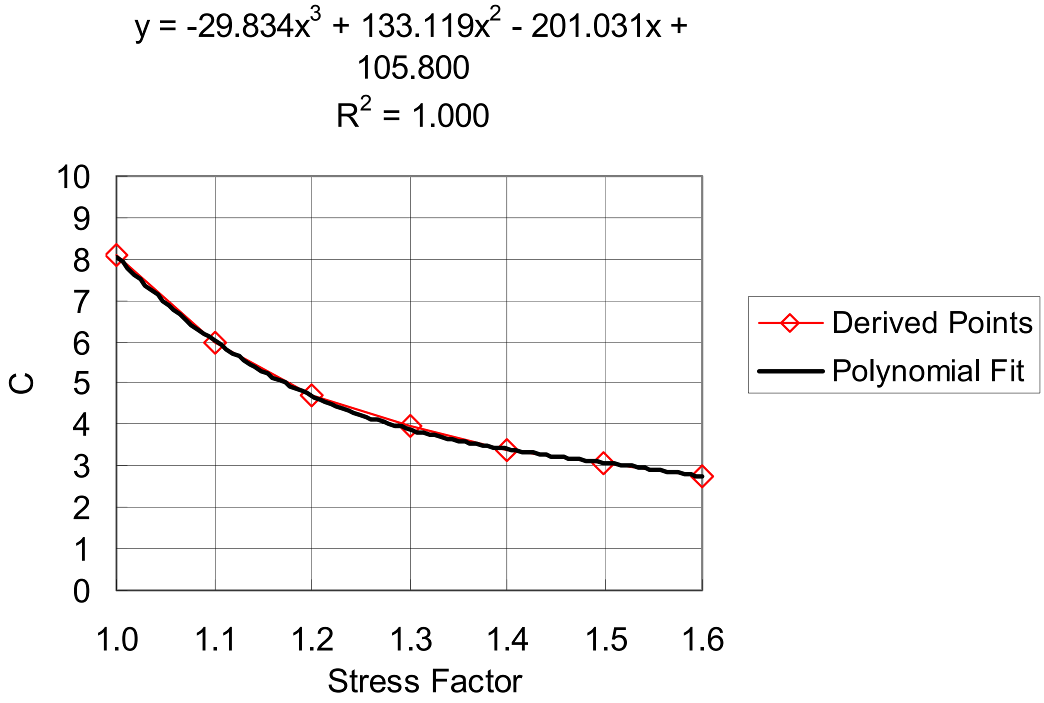
11.NUREG/CR-6235, “Assessment of Short Through-Wall Circumferential Cracks in Pipe,” US Nuclear Regulatory Commission, April 1995.

Table A2-1 Main steam piping property

Subsystem	OD, inches	t, inches	Material	Temp, ºF	Pressure, psig	Axial. Stress, ksi
Main Steam Line	32	1.5	SA-336 Gr. 6	535	907	4.181

Table A2-2 SA-333 Grade 6 Properties at 550ºF

Property	Value
Modulus of Elasticity, ksi	27,000
Minimum S_y, ksi	27.65
Minimum S_{ult}, ksi	60.0
Minimum Flow Stress S_{flow}, ksi	43.825
α_y	1.953
α_{flow}	10.719
n	4.697



Notes: J (in-kips/in) = C $\Delta a^{0.6}$ where Δa has units of inches
Actual base material minimum ratio of $\sigma_y / \sigma_{y,\text{Code Min}}$ or $\sigma_{flow} / \sigma_{flow,\text{Code Min}}$

Figure A2-1 Coefficient C for JR Curves

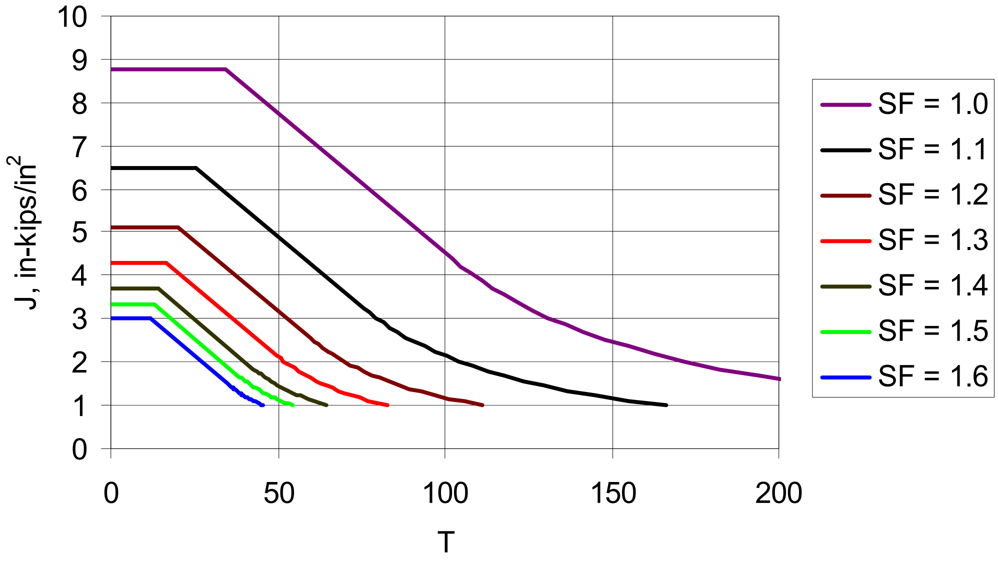


Figure A2-2 JT Curves

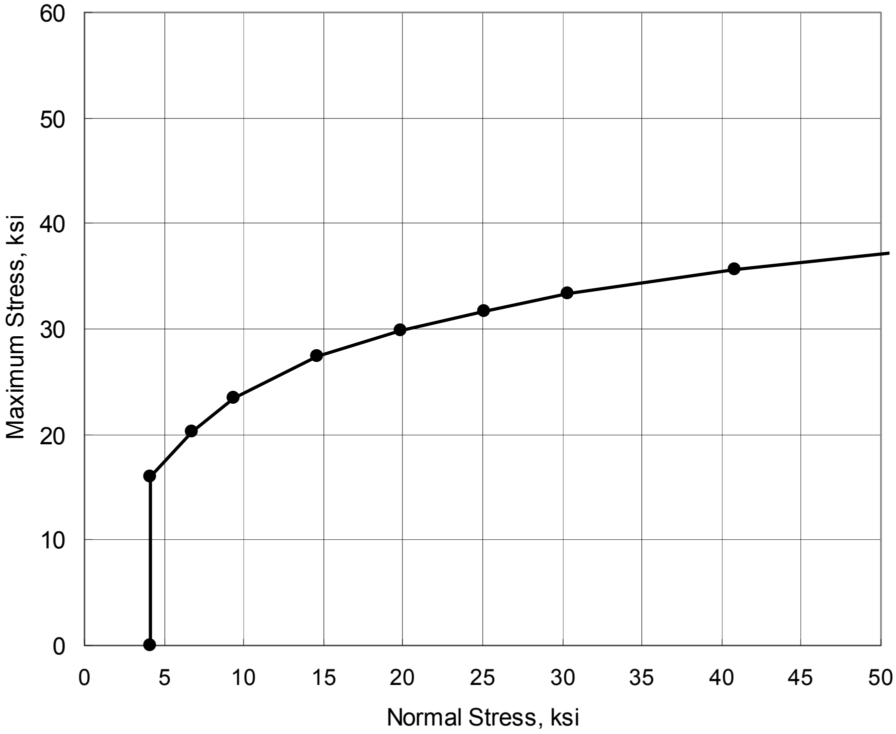


Figure A2-3 BAC for Main Steam Line

Table A2-3 The tabulated BAC points

Normal Stress, ksi	Maximum Stress, ksi
4.18	0.00
4.18	15.92
6.80	20.27
9.41	23.47
14.65	27.46
19.88	29.87
25.11	31.64
30.34	33.33
40.81	35.70
51.27	37.31

Figure A2-4 Seismic floor response curve of STD (1/12)
Main Steam Line (MS01-02) FRS for SG Nozzle
X(EW) direction (damping 4.0%)

Figure A2-4 Seismic floor response curve for STD (2/12)
Main Steam Line (MS01-02) FRS for SG Nozzle
Y(NS) direction (damping 4.0%)

Figure A2-4 Seismic floor response curve of STD (3/12)
Main Steam Line (MS01-02) FRS for SG Nozzle
Z(Vert.) direction (damping 4.0%)

Figure A2-4 Seismic floor response curve of STD (4/12)
Main Steam Line (MS01-02) FRS for Piping Supports (IC61,62-IC05)
X(EW) direction (damping 4.0%)

Figure A2-4 Seismic floor response curve of STD (5/12)
Main Steam Line (MS01-02) FRS for Piping Supports (IC61,62-IC05)
Y(NS) direction (damping 4.0%)

Figure A2-4 Seismic floor response curve of STD (6/12)
Main Steam Line (MS01-02) FRS for Piping Supports (IC61,62-IC05)
Z(Vert.) direction (damping 4.0%)

Figure A2-4 Seismic floor response curve of STD (7/12)
Main Steam Line (MS01-02) FRS for Piping Supports (IC71,72-IC61,62)
X(EW) direction (damping 4.0%)

Figure A2-4 Seismic floor response curve of STD (8/12)
Main Steam Line (MS01-02) FRS for Piping Supports (IC71,72-IC61,62)
Y(NS) direction (damping 4.0%)

Figure A2-4 Seismic floor response curve of STD (9/12)
Main Steam Line (MS01-02) FRS for Piping Supports (IC71,72-IC61,62)
Z(Vert.) direction (damping 4.0%)

Figure A2-4 Seismic floor response curve of STD (10/12)
Main Steam Line (MS01-02) FRS for CV Penetration
X(EW) direction (damping 4.0%)

Figure A2-4 Seismic floor response curve of STD (11/12)
Main Steam Line (MS01-02) FRS for CV Penetration
Y(NS) direction (damping 4.0%)

Figure A2-4 Seismic floor response curve of STD (12/12)
Main Steam Line (MS01-02) FRS for CV Penetration
Z(Vert.) direction (damping 4.0%)

Figure A2-5 Seismic floor response curve of NA3 (1/12)
Main Steam Line (MS01-02) FRS for SG Nozzle
X(EW) direction (damping 4.0%)

Figure A2-5 Seismic floor response curve of NA3 (2/12)
Main Steam Line (MS01-02) FRS for SG Nozzle
Y(NS) direction (damping 4.0%)

Figure A2-5 Seismic floor response curve of NA3 (3/12)
Main Steam Line (MS01-02) FRS for SG Nozzle
Z(Vert.) direction (damping 4.0%)

Figure A2-5 Seismic floor response curve of NA3 (4/12)
Main Steam Line (MS01-02) FRS for Piping Supports (IC61,62-IC05)
X(EW) direction (damping 4.0%)

Figure A2-5 Seismic floor response curve of NA3 (5/12)
Main Steam Line (MS01-02) FRS for Piping Supports (IC61,62-IC05)
Y(NS) direction (damping 4.0%)

Figure A2-5 Seismic floor response curve of NA3 (6/12)
Main Steam Line (MS01-02) FRS for Piping Supports (IC61,62-IC05)
Z(Vert.) direction (damping 4.0%)

Figure A2-5 Seismic floor response curve of NA3 (7/12)
Main Steam Line (MS01-02) FRS for Piping Supports (IC71,72-IC61,62)
X(EW) direction (damping 4.0%)

Figure A2-5 Seismic floor response curve of NA3 (8/12)
Main Steam Line (MS01-02) FRS for Piping Supports (IC71,72-IC61,62)
Y(NS) direction (damping 4.0%)

Figure A2-5 Seismic floor response curve of NA3 (9/12)
Main Steam Line (MS01-02) FRS for Piping Supports (IC71,72-IC61,62)
Z(Vert.) direction (damping 4.0%)

Figure A2-5 Seismic floor response curve of NA3 (10/12)
Main Steam Line (MS01-02) FRS for CV Penetration
X(EW) direction (damping 4.0%)

Figure A2-5 Seismic floor response curve of NA3 (11/12)
Main Steam Line (MS01-02) FRS for CV Penetration
Y(NS) direction (damping 4.0%)

Figure A2-5 Seismic floor response curve of NA3 (12/12)
Main Steam Line (MS01-02) FRS for CV Penetration
Z(Vert.) direction (damping 4.0%)

Table A2-4 Seismic anchor displacement input data of STD (1/3)

Table A2-4 Seismic anchor displacement input data of STD (2/3)

Table A2-4 Seismic anchor displacement input data of STD (3/3)

Table A2-5 Seismic anchor displacement input data of NA3 (1/3)

Table A2-5 Seismic anchor displacement input data of NA3 (2/3)

Table A2-5 Seismic anchor displacement input data of NA3 (3/3)

Figure A2-6 LBB evaluation results for MS01 (STD)

Figure A2-7 LBB evaluation results for MS01 (NA3)

Figure A2-8 LBB evaluation results for MS02 (STD)

Figure A2-9 LBB evaluation results for MS02 (NA3)