Summary of Stress Analysis Results for the US-APWR Pressurizer

Non-proprietary Version

March 2011

Revision History

Revision	Page	Description
0	All	Original Issue
1	Abstract	Change sentences.
	Table of Contents	Revise table of contents and page numbers.
	List of Tables	Revise list of tables and page numbers.
	List of Figures	Revise list of figures and page numbers.
	1.0 Introduction	Change sentences.
	2.0 Summary of results	Delete analysis results of Surge Nozzle, Spray Line Nozzle, Upper Head & Upper Shell Transition, Safety Valve Nozzle and Safety Depressurization Valve Nozzle, and revise analysis results.
	3.0 Conclusions	Change sentences.
	7.2 Material	Arrange tables for material property.
	7.3 Loads, Load Combinations, and Transients	Delete loads of Surge Nozzle, Spray Line Nozzle, Safety Valve Nozzle and Safety Depressurization Valve Nozzle, and revise loads and transients.
	8.2 Stress Analysis	Add program.
	8.3 Fatigue Analysis Model and Method	Change sentences.
	9.0 Computer Programs Used	Revise programs and add program.
	10.0 Structual Analysis Results	Delete analysis results of Surge Nozzle, Spray Line Nozzle, Upper Head & Upper Shell Transition, Safety Valve Nozzle and Safety Depressurization Valve Nozzle, and revise analysis results.
	12.0 References	Revise references.

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

Abstract

This report contains a summary of the structural evaluation of the four Pressurizer (PZR) parts.

The evaluations performed were based on the loading conditions defined in the US-APWR PZR Design Specification (Reference 4) and on the design procedures per the 2001 Edition of Section III of the ASME Boiler & Pressure Vessel Code up to and including the 2003 addenda, referred to as the ASME Code of Reference, Section III (Reference 1).

The analyses and results presented demonstrate that the four parts of the PZR that were evaluated satisfy all of the applicable structural limits of the ASME Code of Reference.

Table of Contents

List of Tables

List of Figures

List of Acronyms

The following list defines the acronyms used in this document.

CUF	Cumulative Usage Factor for fatigue
DCD	Design Control Document
FEA	Finite Element Analysis
FSRF	Fatigue Strength Reduction Factor
LOCA	Loss-of-Coolant Accident
PZR	Pressurizer
RCS	Reactor Coolant System
SLB	Steam Line Break
SRSS	Square Root of the Sum of the Squares
SSE	Safe Shutdown Earthquake

1.0 INTRODUCTION

This Technical Report contains a summary of the stress analysis results for the US-APWR Pressurizer (PZR). The content of this report follows the ASME guidelines for Design Reports (Section III Division 1 Appendix C).

The pressurizer is a vertically mounted cylindrical vessel with hemispherical heads. It is constructed of low-alloy steel and clad with austenitic stainless steel. The pressurizer has bottom-mounted heaters to heat the coolant in the pressurizer and has an upper head-mounted spray line nozzle to add coolant from the cold leg piping to decrease the Reactor Coolant System (RCS) pressure.

The electric immersion heaters are vertically oriented and pass through the bottom head. The heater sheath is welded to the heater sleeve end that protrudes from the bottom head. The heater sleeve is welded to the inner surface of the bottom head. The bottom head also has a surge nozzle that connects to the RCS hot leg.

At the upper head, there are four safety valve nozzles for overpressure protection, a safety depressurization valve nozzle, a spray line nozzle, and a manway. In the vertical shell are small nozzles for primary water sampling and for pressure, temperature, and level instrumentation.

Figure 1-1 shows the general configuration of the US-APWR Pressurizer.

This report provides structural evaluations for four Pressurizer parts. The four evaluated PZR parts are listed in Table 2-1. This Technical Report summarizes the stress results based upon detailed analyses that demonstrate the validity of the PZR component to meet the requirements of the Design Specification (Reference 4).

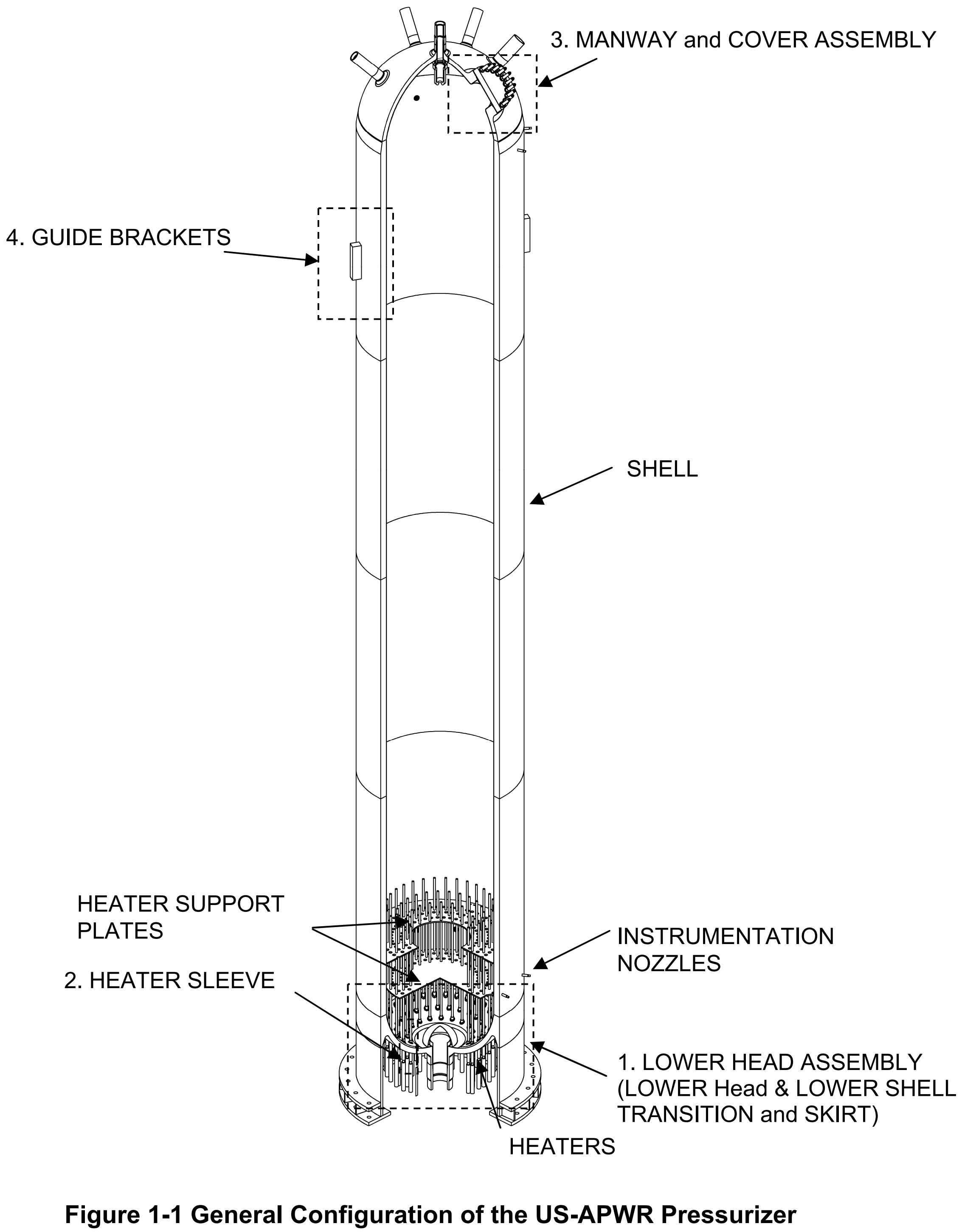

Figure 1-1 General Configuration of the US-APWR Pressurizer

2.0 SUMMARY OF RESULTS

The four evaluated parts of the Pressurizer, along with the most limiting results in each, are listed in Table 2-1 below. The structural analysis results for each of these parts are provided in Section 10.

Table 2-1 Summary of Most Limiting Stress Ratios and Fatigue Usage Factors

Section	Evaluated Part	Max Stress / Allowable Ratio [1]	Highest Fatigue [2] Usage Factor
10.1	Lower Head & Lower Shell Transition & Skirt		
10.2	Heater Sleeve Weld Region		
10.3	Manway		
10.4	Guide Bracket		

Note-1: The allowable ratio is the "ratio" of the calculated stress intensity to the allowable stress intensity. Therefore, any ratio less than or equal to 1.0 is acceptable.

$$\text{Ratio} = \frac{\text{Calculated} \cdot \text{Stress} \cdot \text{Intensity}}{\text{Allowable} \cdot \text{Stress} \cdot \text{Intensity}}$$

Note-2: The fatigue calculations performed in this report meet the requirements of the ASME Code of Reference. Environmental fatigue per RG 1.207 will be evaluated separately.

Note-3: The primary plus secondary stress ratio excluding thermal bending

Note-4: CUF for stud bolt

3.0 CONCLUSIONS

The US-APWR PZR is designed to the requirements of the ASME Boiler and Pressure Vessel Code, 2001 Edition up to and including the 2003 Addenda for the Design, Service Loadings, Operating Conditions, and Test Conditions as specified in the Design Specification (Reference 4).

4.0 NOMENCLATURE

Symbol	Unit	Definition
P_m	ksi	General Primary Membrane Stress
P_L	ksi	Local Primary Membrane Stress
P_b	ksi	Primary Bending Stress
Q	ksi	Secondary Stress
S_m	ksi	Design Stress Intensity
S_y	ksi	Yield Stress
S_u	ksi	Tensile Strength
A_b	in^2	Actual Total Cross-Sectional Area of Bolts at Root of Thread or Section of Least Diameter Under Stress
A_m	in^2	Required Total Design Cross-Sectional Area of Bolts, taken as the greater of A_{m1} and A_{m2}
S_t	ksi	Averaged Stress for Bolt (neglecting stress concentration)
$S_t + S_b$	ksi	Tension plus Bending Stress for Bolt (neglecting stress concentration)
y_A	-	Thermal Ratcheting Factor
SS	ksi	Thermal Stress Range
α	-	Shape Factor: the ratio of the load set producing a fully plastic section of the load set producing initial yielding in the extreme fibers of the section
P	-	Design Pressure
DL	-	Dead Load
1/3 SSE	-	Level B Service Loading Earthquake
SSE	-	Safe Shutdown Earthquake

5.0 ASSUMPTIONS AND OPEN ITEMS

5.1 Assumptions

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

1. The inside diameter is taken as the drawing nominal value.
2. The wall thickness is the drawing nominal value.
3. For particular cases, cladding less than 10% of the total thickness is not considered in the stress analysis.
4. The corrosion allowance is zero.

5.2 Open Items

There are no open items in this Technical Report.

6.0 ACCEPTANCE CRITERIA

The stress intensity acceptance criteria for Class 1 components are specified in NB-3220, NB-3230 and Appendix F of Section III. Table 6-1 lists the stress limits (other than bolts) and Table 6-2 lists the stress limits for bolts. Table 6-3 lists the stress limits for skirt.

Table 6-1 Class 1 Component Stress Limits (other than bolts and Skirt)

Condition	Stress Category	Stress Limits	Remarks
Design	P_m	S_m	NB-3221.1
	P_L	1.5 S_m	NB-3221.2
	$P_L + P_b$	$\alpha\ S_m$[1) 2)] or 1.5 S_m	NB-3221.3
	Bearing Stress	S_y[6)] or 1.5 S_y[6)]	NB-3227.1(a)
	Shear Stress	0.6 S_m	NB-3227.1(b)
	Pure Shear Stress	0.6 S_m	NB-3227.2(a)
	Triaxial Sress[4)]	4 S_m	NB-3227.4
Level A & B	$P_L + P_b + Q$	3 S_m	NB-3222.2
	Thermal Ratchet, SS[5)]	$S_y \times y_A$	NB-3222.5
	Usage Factor	1.0	NB-3222.4
	Bearing Stress	S_y[6)] or 1.5 Sy[6)]	NB-3227.1(c)
	Shear Stress	0.6 S_m	NB-3227.1(b)
	Pure Shear Stress	0.6 S_m	NB-3227.2(a)
	Triaxial Sress[4)]	4 S_m	NB-3227.4
Level B	P_m	1.1 S_m	NB-3223
	P_L	1.5 (1.1 Sm)	NB-3223
	$P_L + P_b$	α (1.1 S_m)[1) 2)] or 1.5 (1.1S_m)	NB-3223
Level C	P_m	Max (1.2 S_m, S_y) Max (1.1 S_m, 0.9 S_y)[3)]	NB-3224.1
	P_L	Max (1.8 S_m, 1.5 S_y)	NB-3224.1
	$P_L + P_b$	Max (α (1.2 S_m), $\alpha\ S_y$)[1) 2)] or Max (1.8 S_m, 1.5 S_y)	NB-3224.1
	Bearing Stress	S_y[6)] or 1.5 S_y[6)]	NB-3227.1(a)
	Shear Stress	0.6 S_m	NB-3227.1(b)
	Pure Shear Stress	0.6 S_m	NB-3227.2(a)
	Triaxial Sress[4)]	4.8 S_m	NB-3224.3
Level D	P_m	For ferritic materials, 0.7 S_u For austenitic and high alloy steels, Min (2.4 S_m, 0.7 S_u)	NB-3225 (Appendix F-1331.1)
	P_L	For ferritic materials, 1.5 (0.7 S_u) For austenitic and high alloy steels, 1.5 Min (2.4 S_m, 0.7 S_u)	
	$P_L + P_b$	For ferritic materials, 1.5 (0.7 S_u) For austenitic and high alloy steels, 1.5 Min (2.4 S_m, 0.7 S_u)	
	Pure Shear	0.42 S_u	
Test	P_m	0.9 S_y	NB-3226
	$P_m + P_b$	(1.35 S_y) - for $P_m \leq 0.67\ S_y$ (or 0.9 $\alpha\ S_y$ for non-rectangular sections) (2.15 S_y -1.2 P_m) - for 0.67 $S_y \leq P_m \leq 0.9\ S_y$	
	Bearing Stress	S_y[6)] or 1.5 S_y[6)]	NB-3227.1(a)

Table 6-1 Class 1 Component Stress Limits (other than bolts and Skirt)

Condition	Stress Category	Stress Limits	Remarks
	Shear Stress	0.6 S_m	NB-3227.1(b)
	Pure Shear Stress	0.6 S_m	NB-3227.2(a)
	Triaxial Sress 4)	4 S_m	NB-3227.4
Note-1	The shape factor of α for solid rectangular sections is 1.5, α shall not exceed 1.5.		
Note-2	"α" is considered where stresses are classified as primary bending		
Note-3	The stress limits for pressure loading alone for ferritic material.		
Note-4	NB-3227.4 states that the Triaxial Stress limit is 4 S_m and does not apply to Level D. NB-3224.3 states the Level C limit is 4.8 S_m.		
Note-5	NB-3222.5 requires evaluation of Thermal Stress Ratcheting for Level A Service Loads. In all cases where elastic analysis indicates that the primary membrane stress is less than S_m and the primary plus secondary stress is less than 3 S_m, then thermal stress ratcheting will not occur.		
Note-6	S_y when the distance to a free edge is less than the distance over which the bearing load is applied; 1.5 S_y when the distance to a free edge is larger.		

Table 6-2 Class 1 Bolt Stress Limits

Condition	Stress Category	Stress Limits	Remarks
Design	A_b	A_m	NB-3231, E-1000
Level A & B	Average Service Stress 1), S_t	2 S_m	NB-3232.1
	Max Service Stress 1), $S_t + S_b$	3 S_m	NB-3232.2
	Fatigue Usage Factor 2)	1.0	NB-3232.3
Level C	Average Service Stress 1), S_t	2 S_m	NB-3234
	Max Service Stress 1), $S_t + S_b$	3 S_m	NB-3234
Level D	Average Tensile Stress 3), S_t	Min (S_y, 0.7 S_u)	NB-3235 & F-1335.1
	Max Tensile Stress 3), $S_t + S_b$	S_u	NB-3235 & F-1335.1
	Average bolt shear	Min (0.6 S_y, 0.42 S_u)	F-1335.2
	Combined tensile and shear	$f_t^2/F_{tb}^2 + f_v^2/F_{vb}^2 \le 1$ 4)	F-1335.3
	Distance from bolt center to edge	d (0.5 + 1.2 fp / S_u) 5)	F-1335.4(a)
	Nominal bearing stress	2.1 S_u	F-1335.4(b)
Note-1	Includes preload, pressure, and differential thermal expansion, excludes stress concentrations.		
Note-2	Includes a fatigue strength reduction factor of 4 for the threads.		
Note-3	Includes preload, pressure, differential thermal expansion, and prying action produced by deformation of the connected parts, excludes stress concentrations.		
Note-4	f_t=computed tensile stress, f_v=computed shear stress, F_{tb}=allowable tensile stress at operating temperature, F_{vb}=allowable shear stress at operating temperature		
Note-5	d= nominal bolt diameter; fp = nominal bearing stress		

Table 6-3 Class 1 Support Stress Limits (used for Skirt)

Condition	Stress Category	Stress Limits	Remarks
Design	P_m	S_m	NF-3221.1
	$P_m + P_b$	$1.5\ S_m$	NF-3221.1
Level A	P_m	S_m	NF-3221.2
	$P_m + P_b$	$1.5\ S_m$	NF-3221.2
	$P_m + P_b + Q$ 1)	Min ($2\ S_y$, S_u)	NF-3221.2
Level B	P_m	$1.33\ S_m$	NF-3221.2
	$P_m + P_b$	1.5 ($1.33\ S_m$)	NF-3221.2
	$P_m + P_b + Q$ 1)	Min ($2\ S_y$, S_u)	NF-3221.2
Level C	P_m	Min ($1.5\ S_m$, $0.7\ S_u$)	NF-3221.2
	$P_m + P_b$	1.5Min (($1.5\ S_m$) , 0.7 Su)	NF-3221.2
Level D	P_m	Min [Max ($1.2\ S_y$, $1.5\ S_m$), $0.7\ S_u$]	F- 1332.1
	$P_m + P_b$	1.5 Min [Max ($1.2\ S_y$, $1.5\ S_m$), $0.7\ S_u$]	F- 1332.2
Test	P_m	$1.33\ S_m$	NF-3221.3
	$P_m + P_b$	1.5 ($1.33\ S_m$)	NF-3221.3
Note-1	Q: Secondary stress does not include thermal stress per Table NF-3522(b)-1		

7.0 DESIGN INPUT

7.1 Geometry

The US-APWR PZR design drawings used to supply dimensions for the stress analysis are listed in Table 7-1. Figures describing the detailed geometry and dimensions of the parts evaluated are provided in Section 10.

Table 7-1 US-APWR Pressurizer Design Drawing List

No.	Drawing Title	Drawing Number
1	Pressurizer Design drawings	N0-F500A01

7.2 Material

The materials for the pressure boundary and other parts are listed in Table 7-2.

Table 7-2 Materials of Construction

Part or Assembly	Material
Heads	SA-508 Grade 3 Class 1
Shells	SA-508 Grade 3 Class 1
Nozzles	SA-508 Grade 3 Class 1
Nozzle Safe Ends	SA-182 Grade F316
Heater Sleeve	SA-182 Grade F316
Manway Pad	SA-508 Grade 3 Class 1
Manway Cover	SA-533 Type B Class 2
Manway Stud Bolts	SA-193 Grade B7
Manway Nuts	SA-194 Grade 4
Guide Brackets	SA-533 Type B Class 1
Skirt	SA-516 Grade 70

The material strength properties used in the stress analyses are provided in Table 7-3 through 7-9. The strength properties were obtained from ASME Section II (Reference 2).

Table 7-3 Material Properties for SA-508 Grade 3, Class 1

Temperature, °F	S_m	S_y	S_u
70	26.7	50.0	80.0
100	26.7	50.0	80.0
200	26.7	47.0	80.0
300	26.7	45.5	80.0
400	26.7	44.2	80.0
500	26.7	43.2	80.0
600	26.7	42.1	80.0
650	26.7	41.5	80.0

Table 7-4 Material Properties for SA-533 Type B, Class 1

Temperature, °F	S_m	S_y	S_u
70	26.7	50.0	80.0
100	26.7	50.0	80.0
200	26.7	47.0	80.0
300	26.7	45.5	80.0
400	26.7	44.2	80.0
500	26.7	43.2	80.0
600	26.7	42.1	80.0
650	26.7	41.5	80.0

Table 7-5 Material Properties for SA-533 Type B Class 2

Temperature, °F	S_m	S_y	S_u
70	30.0	70.0	90.0
100	30.0	70.0	90.0
200	30.0	65.9	90.0
300	30.0	63.7	90.0
400	30.0	61.9	90.0
500	30.0	60.4	90.0
600	30.0	58.9	90.0
650	30.0	58.0	90.0

Table 7-6 Material Properties for SA-182 Grade F316

Temperature, °F	S_m	S_y	S_u
70	20.0	30.0	70.0
100	20.0	30.0	70.0
200	20.0	25.9	70.0
300	20.0	23.4	68.0
400	19.3	21.4	67.1
500	18.0	20.0	67.0
600	17.0	18.9	67.0
650	16.6	18.5	67.0

Table 7-7 Material Properties for SA-182 Grade F304

Temperature, °F	S_m	S_y	S_u
70	20.0	30.0	70.0
100	20.0	30.0	70.0
200	20.0	25.0	66.3
300	20.0	22.4	61.8
400	18.6	20.7	59.7
500	17.5	19.4	59.2
600	16.6	18.4	59.2
650	16.2	18.0	59.2

Table 7-8 Material Properties for SA-193 Gr. B7 & SA-194 Gr. 4

Temperature, °F	S_m	S_y	S_u
70	35.0	105.0	125.0
100	35.0	105.0	125.0
200	32.6	98.0	125.0
300	31.4	94.1	125.0
400	30.5	91.5	125.0
500	29.5	88.5	125.0
600	28.4	85.3	125.0
650	27.7	83.0	124.4

Table 7-9 Material Properties for SA-516 Grade 70

Temperature, °F	S_m	S_y	S_u
70	23.3	38.0	70.0
100	23.3	38.0	70.0
200	23.2	34.8	70.0
300	22.4	33.6	70.0
400	21.6	32.5	70.0
500	20.6	31.0	70.0
600	19.4	29.1	70.0
650	18.8	28.2	70.0

7.3 Loads, Load Combinations, and Transients

The loads, load combinations and transients are defined in Design Specification. The following is a summary of those used for the PZR structural evaluations.

7.3.1 Pressure Loads and Temperature

Table 7-10 Pressures and Temperatures

Parameter	Value
Design pressure	2500 psia (2485 psig)
Design temperature	680°F
Normal operating pressure	2250 psia (2235 psig)
Hydrostatic test pressure	3122 psia (3107 psig)
Minimum hydrostatic test temperature	70°F

7.3.2 External Mechanical Loads

The external loads are dead weight, thermal expansion loads, seismic loads and accident loads. The external loads are considered at the nozzles and supports of the pressure boundary and obtained from the Design Specification (Reference 4).

Tables 7-11 to 7-12 provide the external loads on the PZR. Figures 7-1 to 7-2 show the local coordinate system for the loads.

The bolt preload values for the manway studs used in the analyses were the minimum required bolt load for the test pressure calculated in accordance with Article E-1000 of the ASME Code of Reference.

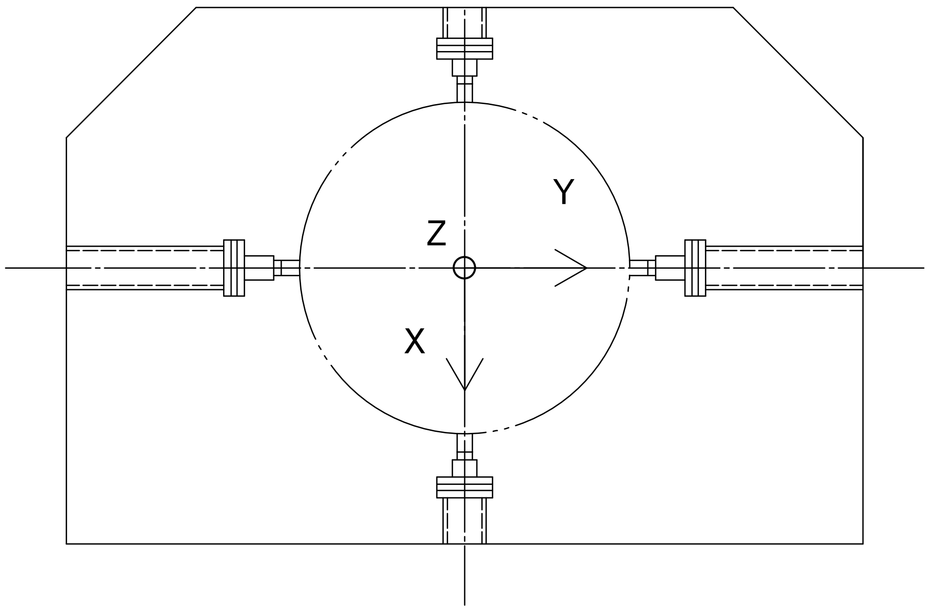

Figure 7-1 Coordinate System for Upper Support

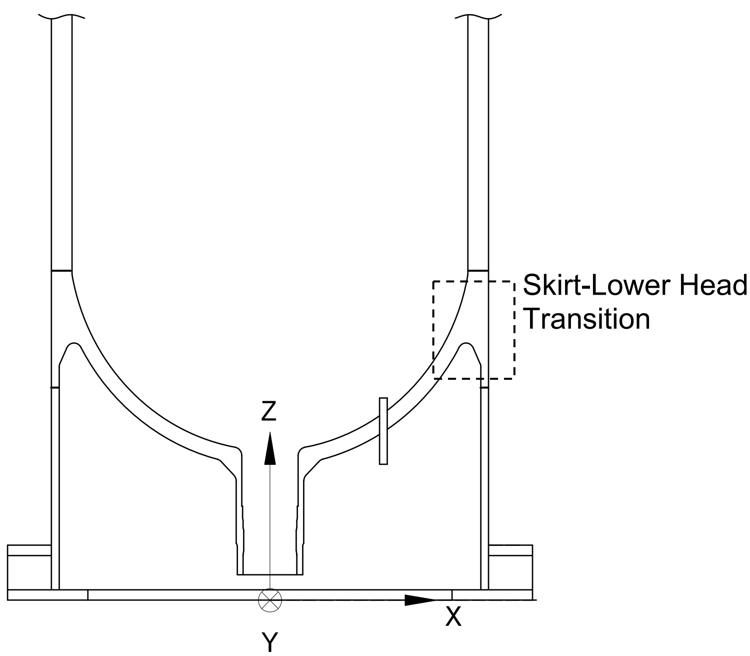

Figure 7-2 Coordinate System for Skirt

Table 7-11 Loads Applied to the Support Bracket

No.	Loading	Fx (kips)	Fy (kips)	Fz (kips)	Mx (kips・in)	My (kips・in)	Mz (kips・in)
1	Dead Weight						
2	Thermal						
3	Seismic (1/3 SSE)						
4	Seismic (SSE)						
5	Accident						

Table 7-12 Loads Applied to the Skirt

No.	Loading		Fx (kips)	Fy (kips)	Fz (kips)	Mx (kips·in)	My (kips·in)	Mz (kips·in)
1	Dead Weight	Lower Shell-Lower Head Weld Joint						
		Skirt-Lower Head Transition (Skirt)						
		Skirt-Lower Head Transition (Lower Head)						
		Base Plate						
2	Thermal							
3	Seismic (1/3 SSE)	Lower Shell-Lower Head Weld Joint						
		Skirt-Lower Head Transition (Skirt)						
		Skirt-Lower Head Transition (Lower Head)						
		Base Plate						
4	Seismic (SSE)	Lower Shell-Lower Head Weld Joint						
		Skirt-Lower Head Transition (Skirt)						
		Skirt-Lower Head Transition (Lower Head)						
		Base Plate						
5	Accident							

7.3.3 Thermal and Pressure Transient Loads

The design transients used in the structural evaluations are listed in Table 7-13. These transients were determined based on a 60-year plant operating period and were classified into the ASME Level A, Level B, Level C, Level D service conditions, and Test conditions, depending on the expected frequency of occurrence and severity of the event.

For the tables and figures stated in the Table 7-13, see Reference 4.

Table 7-13 Pressurizer design transients (1/3)

Mark	Transient		(a) Occurrence	Remark
Level A				
I-a	Plant heat-up		120	-
I-b-1	Plant cooldown (2235~400psig)		120	-
I-b-2	Plant cooldown (under 400psig)		120	-
I-c-1	Ramp load increase between 15% and 100% of full power (5% of full power per minute)		600	-
I-c-2	Ramp load increase between 50% and 100% of full power (5% of full power per minute)		19,200	-
I-d-1	Ramp load decrease between 15% and 100% of full power (5% of full power per minute)		600	-
I-d-2	Ramp load decrease between 50% and 100% of full power (5% of full power per minute)		19,200	-
I-e	Step load increase of 10% of full power		600	-
I-f	Step load decrease of 10% of full power		600	-
I-g	Large step load decrease with turbine bypass		60	-
I-h	Steady-state fluctuation and load regulation	i)Steady-state fluctuation	1×10^{6}	-
		ii)Load regulation	8×10^{5} 1.6×10^{6}(Note1)	-
I-i	Main feedwater cycling		2,100	-
I-m	Reactor Coolant Pump startup		3,000	-
I-n	Reactor Coolant Pump shutdown		3,000	-
I-p	Primary leakage test		120	-
I-q	Turbine roll test		10	-
I-r	Boron Concentration		39,600	-

(Note1) This occurrence is applied for Surge Nozzle.

Table 7-13 Pressurizer design transients (2/3)

Mark	Transient	(a) Occurrence	Remark
Level B			
II-a	Loss of load	60	-
II-b	Loss of offsite power	60	-
II-c	Partial loss of reactor coolant flow	30	-
II-d	RT from full power		
	i) With no inadvertent cooldown	60	-
	ii) With cooldown and no safety injection	30	-
	iii) With cooldown and safety injection	10	-
II-e	Inadvertent RCS depressurization		
	i) Umbrella case	30	-
	ii) Inadvertent auxiliary spray	15	-
II-f	Control rod drop	30	-
II-g	Inadvertent safeguards actuation	30	-
II-h	Emergency feedwater cycling	700	-
II-i	Cold over-pressure		
	i) mass input	30	-
	ii) heat input	30	-
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	Use the figure of the transient of Loss of offsite power.
II-m	Safe shutdown	-	Be covered with the transient of Plant cooldown

Table 7-13 Pressurizer design transients (3/3)

Mark	Transient	(a) Occurrence	Remark
Level C			
III-a	Reactor coolant pipe break (Small LOCA)	5	-
III-b	Small steam line break	5	-
III-c	Complete loss of flow	5	-
III-d	Small feedwater line break	5	-
III-e	SG tube rupture	5	-
Level D			
IV-a	Reactor coolant pipe break (Large LOCA)	1	-
IV-b	Large steam line break	1	-
IV-c	RCP locked rotor	1	-
IV-d	Control rod ejection	1	-
IV-e	Large feedwater line break	1	-
Test			
V-a	Primary-side hydrostatic test	10	-
Others			
VI-a	Bolt Tensioning(Note2)	120	-

(Note 2) This transient is applied for Manway.

7.3.4 Load Combinations

The loading conditions consist of various combinations of pressure, temperature and external loads. The load combinations considered in the analyses are listed in the table 7-14.

The names used for the external loads refer directly to the names specified in Tables 7-11 to 7-12.

Table 7-14 Load Combinations

System Operating Condition	Service Stress Limit	Service Loading Combination
Design	Design	Design Pressure
		Dead Weight Loads
		Mechanical Loads
		Thermal Loads(1)
Normal	Level A	Level A Thermal & Pressure Transients
		Dead Weight Loads
		Mechanical Loads
		Thermal Loads(1)
Upset	Level B	Level B Maximum Pressure(2)
		Level B Thermal & Pressure Transients
		Dead Weight Loads
		Mechanical Loads
		Thermal Loads(1)
		Seismic(1/3 SSE) Loads
Emergency	Level C	Level C Maximum Pressure
		Level C Thermal & Pressure Transients(3)
		Dead Weight Loads
		Mechanical Loads
		Thermal Loads(1)
Faulted	Level D	Level D Maximum Pressure
		Dead Weight Loads
		Mechanical Loads
		Thermal Loads(1)
		±SRSS(Seismic(SSE) Loads + Accident Loads(4))
Test	Test	Dead Weight Loads
		Hydrostatic Test Pressure

Note-1: Applied for the nozzle within the limits of reinforcement in the primary stress evaluation.

Note-2: Applied for the primary stress evaluation.

Note-3: Applied for the bolts instead of Maximum Pressure.

Note-4: If more than one Accident Loads, each are to be analyzed separately.

8.0 METHODOLOGY

The ABAQUS computer program was used to determine loads, temperature distributions, stresses, and deformations of the structure. ABAQUS is a general purpose finite element computer program used by MHI in the design and analysis of nuclear components. ABAQUS is available in the public domain and has been used by MHI for U.S. replacement steam generator and replacement RV closure head projects.

8.1 Heat Transfer Coefficients and Thermal Analysis

Heat transfer coefficients on the inner and outer surfaces of the component are required to define the temperature distributions during transients. Classical Handbook heat transfer equations (References 6) were used to calculate the heat transfer coefficients.

Finite element thermal analyses were performed for all Level A and Level B transients to define the time-dependent temperature distributions of the structure. The RCS fluid temperature versus time curves were applied to all wetted surfaces with appropriate heat transfer coefficients as discussed above. The outside surfaces under the vessel insulation were considered adiabatic.

8.2 Stress Analysis

Finite element stress analyses were performed for given loads and boundary conditions. The thermal loads were input from the thermal solution into each node of the structural model. The calculation of NB-3200 stress intensities, stress classifications, and stress evaluations were performed using a set of MHI proprietary computer programs (CLASS2D, CLASS3D, EDITSTRS, EVALPRI, EVALSEFAV, RATCHET, ASMETEMP and EB3500). These programs are described in Section 9.

Figure 8-1 shows the stress evaluation process.

CLASS2D and CLASS3D were used to evaluate the stresses resulting from pressure, thermal loads, and externally applied forces and moments. EDITSTRS creates input files for the stress evaluation programs EVALPRI, EVALSEFAV, and RATCHET. EVALPRI and EVALSEFAV quantify the primary stress intensities, quantity the primary plus secondary stress ranges, and perform the fatigue evaluation. The RATCHET program was used for the thermal ratchet evaluation.

Detailed assumptions associated with the finite element model development and mesh refinement are documented in the detailed calculations. Finite element models were verified by hand calculations using handbook equations.

Figure 8-1 Stress Evaluation Process

8.3 Fatigue Analysis Model and Method

The fatigue analysis was performed following the rules of NB-3216.2 and NB-3222.4(e) of ASME Section III. These rules require calculation of the total stress, including the peak stress, to determine the allowable number of stress cycles for the specified Service Loadings at every point in the structure. In some case, such as the root of the J-weld, a fatigue strength reduction factor (FSRF) was used where the peak stress cannot be accurately calculated. In these cases, the factor was applied to the linearized membrane plus bending stress.

The design transients for ASME Level A and B service conditions (Table 7-13) were used in the evaluation of fatigue caused by cyclic loading. The effect of 300 cycles of a 1/3 SSE seismic event was also included in the evaluation of fatigue, treated as a Level B service condition. The number of cycles assumed for the 1/3 SSE seismic event was based on a fatigue usage factor equivalent to that for a single SSE event of 20 cycles[ ] bolt tensioning cycles were used in the analysis.

9.0 COMPUTER PROGRAMS USED

Refer to Figure 8-1 for a visual description of the Stress Evaluation Process. The table below provides a brief description of each of the computer programs used.

Table 9-1 Computer Program Description

No.	Program Name	Version	Description
1	ABAQUS	6.7-1	ABAQUS is a general purpose finite element computer Code that performs a wide range of linear and nonlinear engineering simulations
2	CLASS2D	4.0	CLASS2D is an MHI Code for classifying the stresses for axisymmetric models
3	CLASS3D	4.0	CLASS3D is an MHI Code for classifying the stresses for 3D solid models
4	EDITSTRS	4.0	EDITSTRS is an MHI Code that creates input files for the stress evaluation programs
5	EVALPRI	7.0	EVALPRI is an MHI Code that performs the primary stress evaluation
6	EVALSEFAV	7.0	EVALSEFAV is an MHI Code program that performs the secondary stress and fatigue evaluation
7	RATCHET	8.0	RATCHET is an MHI Code that evaluates thermal stress ratcheting
8	ASMETEMP	1.0	ASMETEMP is an MHI Code that creates temperature files for the stress evaluation program
9	EB3500	3.0	EB3500 is an MHI Code that performs the general primary membrane stress evaluation

All these computer programs were verified and validated and are maintained 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

10.0 STRUCTURAL ANALYSIS RESULTS

This Section summarizes the results of the analyses for the four parts of the PZR.The stress calculations were performed using a combination of finite element analysis (FEA) and hand calculations. The general element types used for creation of the finite element model were the 20-node quadratic heat transfer brick and the 20-node quadratic brick from the ABAQUS element library, for heat transfer analysis and structural analysis, respectively. The bolts were modeled using a B32 beam element.

The reported results are generally conservative and larger than the actual values if more detailed calculations were performed; but since they all meet the ASME Code allowable limits, further analysis is not necessary.

10.1 Lower Head Assembly (Lower Head & Lower Shell Transition & Skirt)

10.1.1 Modeling and Analysis

Figures 10-1-1 shows the detailed dimensions used for modeling.

Figure 10-1-1 Dimensions of the Cylindrical Skirt

Figure 10-1-2 Finite Element Model for Lower Head Assembly of the Pressurizer

Figure 10-1-3 FEA Model for Lower Head Assembly (Top view)

Figure 10-1-4 Skirt Transition Ring Corner

10.1.2 Stress Results

The stress-to-allowable ratio (calculated stress divided by allowable value), the fatigue cumulative usage factor, and the thermal stress ratchet results for the most limiting locations in the lower head, lower shell and skirt are summarized in Table10-1-1.

Table 10-1-1 Lower Head, lower Shell Transition, Skirt Result Summary

Condition	Part	Stress-to-Allowable Ratio				Fatigue Usage Factor
		Primary Stress			Primary plus Secondary Stress	
		P_m	P_L or P_L+P_b	Triaxial Stress	P_L+P_b+Q	
Design						
Level A / Level B						
Level C						
Level D						
Test						

10.2 Heater Sleeve

10.2.1 Modeling and Analysis

Figure 10-2-1 Lower Head Assembly and Heater Sleeve Arrangement

Figure 10-2-2 Cladding and Heater Sleeve Weld Groove Dimensions

Figure 10-2-3 Heater Sleeve J-Groove Weld Dimensions

Figure 10-2-4 FEA Model for Lower Head & Heater Sleeve

Figure 10-2-5 Finite Element Model for Heater Sleeve J-Groove Weld

10.2.2 Stress Results

The stress-to-allowable ratio (calculated stress divided by allowable value) and the fatigue cumulative usage factor for the most limiting locations in the heater sleeve are summarized in Table10-2-1.

Table 10-2-1 Heater Sleeve Result Summary

Condition	Part	Stress-to-Allowable Ratio				Fatigue Usage Factor	Thermal Ratchet
		Primary Stress			Primary plus Secondary Stress		
		P_m	P_L or P_L+P_b	Triaxial Stress	P_L+P_b+Q		
Design							
Level A / Level B							
Level C							
Level D							
Test							

10.3 Upper Head Assembly (Manway and Cover Assembly)

10.3.1 Modeling and Analysis

Figure 10-3-1 Upper Head Assembly of Pressurizer

Figure 10-3-2 Dimensions of the Manway

Figure 10-3-3 Upper Head FEA Model

Figure 10-3-4 Enlarged view of Upper Head FEA Model

Figure 10-3-5 Manway FEA Model Details

10.3.2 Stress Results

The stress-to-allowable ratio (calculated stress divided by allowable value), the fatigue cumulative usage factor, and the thermal stress ratchet results for the most limiting locations in manway and stud bolt are summarized in Tables 10-3-1 to 10-3-2 respectively.

Table 10-3-1 Manway Result Summary

Condition	Part	Stress-to-Allowable Ratio					Fatigue Usage Factor	Thermal Ratchet
		P_m	P_L or P_L+P_b	Triaxial Stress	Bearing stress	P_L+P_b+Q		
Design								
Level A / Level B								
Level C								
Level D								
Test								

Table 10-3-2 Stud Bolt Result Summary

Condition	Stress Category	Stress-to-Allowable Ratio
Design	Bolt cross sectional area[1)]	
Level A & B	Average Service Stress	
	Max Service Stress	
	Fatigue Usage Factor	
Level C	Average Service Stress	
	Max Service Stress	
Level D	Average Tensile Stress	
	Max Tensile Stress	
	Average bolt shear	
	Combined tensile and shear	
	Distance from bolt center to edge[2)]	
	Nominal bearing stress	

10.4 Guide Bracket

10.4.1 Modeling and Analysis

Figure 10-4-1 Location of the Guide Bracket and Dimensions

Figure 10-4-2 Finite Element Model of the Cylindrical Vessel with Guide Bracket

10.4.2 Stress Results

The stress-to-allowable ratio (calculated stress divided by allowable value), the fatigue cumulative usage factor, and the thermal stress ratchet results for the most limiting locations in guide bracket are summarized in Table 10-4-1.

Table 10-4-1 Guide Bracket Result Summary

Condition	Part	Stress-to-Allowable Ratio				Fatigue Usage Factor	Thermal Ratchet
		Primary Stress			Primary plus Secondary Stress		
		P_m	P_L or P_L+P_b	Triaxial Stress	P_L+P_b+Q		
Design							
Level A / Level B							
evel C							
Level D							
Test							

11.0 FRACTURE MECHANICS ASSESSMENT

When the bulk fluid temperature drops to a low level, brittle failure become a concern. Events that are analyzed include heatup / cooldown and the primary & secondary leak tests. For such cases, non-ductile failure evaluations are carried out for postulated flaws of several sizes. The analysis is normally based on a flaw size equal to 1/4-thickness of the component. In the portions where the flaw size is overly conservative, a smaller flaw size is evaluated. These smaller flaws are selected with consideration of the current inspection techniques. This approach is in accordance with the rules of ASME Section III Appendix-G.

12.0 REFERENCES

1. ASME Boiler and Pressure Vessel Code, Section III, Nuclear Power Plant Components, 2001 Edition through 2003 Addenda
2. ASME Boiler and Pressure Vessel Code, Section II Material Specification, 2001 Edition through 2003 Addenda
3. N0-FB10L01 Rev.3, “US-APWR General Design Specification for Class 1 Components”
4. N0-F500L01, Rev.4, “US-APWR Pressurizer Design Specification”
5. SIMULIA, “ABAQUS Analysis User’s manual”, Version 6.7, 2007
6. Warren M. Rohsenow, James P. Hartnett and Yung I. Cho, “Handbook of Heat Transfer”, Third Edition, McGraw Hill, 1998
7. Unified Inch Screw Threads (UN and UNR Thread Form) ASME B1.1-1989
8. N0-F500A01 Rev.8, “US-APWR Pressurizer Design Drawings”