Summary of Stress Analysis Results for the US-APWR Reactor Coolant Pump

Non-Proprietary Version

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Abstract

This report contains a summary of the results of the structural evaluation of the Reactor Coolant Pump (RCP) parts listed in MHI's commitment letter (Reference 10) concerning the content of this Technical Report.

The results presented are based on calculations that were performed using the loading conditions defined in the US-APWR Reactor Coolant Pump ASME Design Specification (Reference 4) and on the procedures per ASME Boiler & Pressure Vessel Code Section III (Reference 1).

The RCP satisfies all of the applicable structural limits of the 2001 Edition of Section III of the ASME Code up to and including the 2003 addenda (Reference 1).

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List of Acronyms

The following list defines the acronyms used in this document.

DCD	Design Control Document
FEA	Finite Element Analysis
FSRF	Fatigue Strength Reduction Factor
LOCA	Loss-of-Coolant Accident
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RT	Radiographic Examination
SRSS	Square Root of the Sum of the Squares
SSE	Safe Shutdown Earthquake

1.0 INTRODUCTION

This Technical Report was prepared consistent with MHI's commitment letter (Reference 10) in support of the US-APWR DCD review process. It contains a summary of the results of the stress, fatigue and fracture mechanics analyses of the US-APWR Reactor Coolant Pump (RCP). The content of this report follows the ASME guidelines for Design Reports (Section III Division 1 Appendix C).

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

This report provides structural evaluations for eight RCP parts based on the discussion about MHI's commitment letter (Reference 10) concerning the content of this Technical Report. The eight evaluated RCP parts are listed in Table 2-1. This Technical Report summarizes the results of detailed RCP stress, fatigue and fracture mechanics analyses and demonstrates that the RCP components evaluated meet the requirements of the Design Specification (Reference 4).

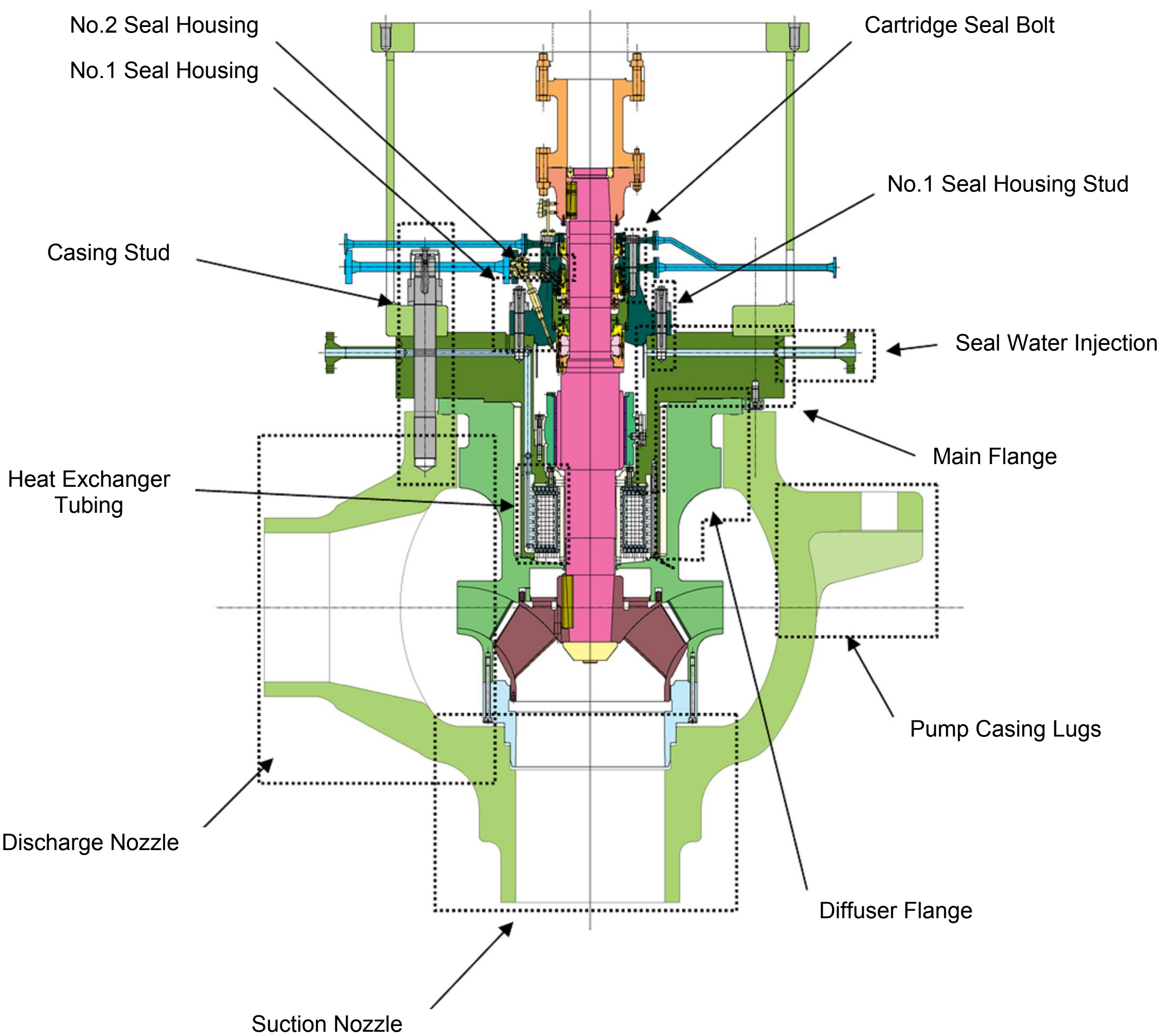


Figure 1-1 Reactor Coolant Pump Component and Evaluated Parts

2.0 SUMMARY OF RESULTS

The structural analysis results for each of these parts are listed in Section 10. The most limiting results for each part that was evaluated are listed in Table 2-1, below.

Table 2-1 Summary of Most Limiting Results

Section	Evaluated Part	Max Stress / Allowable Ratio	Highest Fatigue Usage Factor (note 2)
10.1	Pump Casing Lugs		
10.2	Discharge Nozzle		
10.3	Suction Nozzle		
10.4	Main Flange		
	Studs		
10.5	Seal Housing (No.1 and No.2)		
	Studs		
10.6	Diffuser Flange		
10.7	Heat Exchanger Tubing		
10.8	RCP Seal Water Injection Nozzle		

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.

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

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

Note-3

3.0 CONCLUSIONS

The US-APWR RCP 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).

From the results summarizes in this report and a review of the component design drawings, it is concluded that the US-APWR RCP satisfies all of the requirements of the Design Specification.

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
P	-	Design Pressure
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 used in the 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. The corrosion allowance is assumed to be 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, 3230 and Appendix F of Section III. Table 6-1 lists the stress limits for components other than bolts, and Table 6-2 lists the stress limits for bolts.

Table 6-1 Class 1 Component Stress Limits (other than Bolts)

Condition	Stress Category	Stress Limits	Remarks
Design	P_m	S_m	NB-3221.1
	P_L	$1.5\ S_m$	NB-3221.2
	$P_L + P_b$	αS_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 $1.5\ S_y$ 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-3224.3
Level B	P_m	$1.1\ S_m$	NB-3223
	P_L	$1.5\ (1.1\ S_m)$	NB-3223
	$P_L + P_b$	$\alpha\ (1.1 S_m)$ 1) 2) or $1.5\ (1.1\ S_m)$	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 $(\alpha\ (1.2\ S_m), \alpha\ S_y)$ 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	$0.42\ S_u$	

Condition	Stress Category	Stress Limits	Remarks
Test	P_m	0.9 S_y	NB-3226
	$P_m + P_b$	(1.35 S_y) - for $P_m \le 0.67 S_y$ (or 0.9 α S_y for non-rectangular sections) (2.15 S_y -1.2 P_m) - for 0.67 $S_y < P_m \le 0.9 S_y$	
	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 Sress4)	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.

7.0 DESIGN INPUT

7.1 Geometry

The US-APWR RCP basic drawings used to supply dimensions for the stress analyses are listed in Table 7-1. Figures describing the detailed geometry of the parts evaluated can be found in Section 10.

Table 7-1 RCP Basic Design Drawing List

No.	Drawing Title	Reference Number
1	Reactor Coolant Pump Design Drawings	N0-F600102 Rev.0

7.2 Material

The materials of construction for the RCP pressure boundary and internals are listed in the Table 7-2, below.

Table 7-2 Materials of Construction

Part or Assembly	Material
Casing (including Suction Nozzle, Discharge Nozzle and Casing Lugs)	SA-351 Grade CF8
Main Flange	SA-182 Grade F316
Diffuser Flange	SA-182 Grade F304
No.1 and No.2 Seal Housing	SA-182 Grade F316
Heat Exchanger Tubing	SA-213 Type 316
Pipes	SA-182 Grade F316
Closure Studs, Nuts and Washers	SA-540 Grade B24 Class 4 & Class 2

The material strength properties used in the stress analyses are presented in Tables 7-3 through 7-11, below. These material strength properties were obtained from Section II of the ASME Code (Reference 2).

Table 7-3 Material Properties for SA-351 Grade CF8

Temperature, °F	Sm [ksi]	Sy [ksi]	Su [ksi]
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 7-4 Material Properties for SA-213 Type 316

Temperature, °F	Sm [ksi]	Sy [ksi]	Su [ksi]
70	20.0	30.0	75.0
100	20.0	30.0	75.0
200	20.0	25.9	75.0
300	20.0	23.4	72.9
400	19.3	21.4	71.9
500	18.0	20.0	71.8
600	17.0	18.9	71.8
650	16.6	18.5	71.8

Table 7-5 Material Properties for SA-312 Type 316

Temperature, °F	Sm [ksi]	Sy [ksi]	Su [ksi]
70	20.0	30.0	75.0
100	20.0	30.0	75.0
200	20.0	25.9	75.0
300	20.0	23.4	72.9
400	19.3	21.4	71.9
500	18.0	20.0	71.8
600	17.0	18.9	71.8
650	16.6	18.5	71.8

Table 7-6 Material Properties for SA-182 Grade F316($t \leq 5$)

Temperature, °F	Sm [ksi]	Sy [ksi]	Su [ksi]
70	20.0	30.0	75.0
100	20.0	30.0	75.0
200	20.0	25.5	75.0
300	20.0	22.9	70.7
400	18.9	21.0	67.1
500	17.5	19.5	64.6
600	16.5	18.3	63.3
650	16.0	17.8	62.8

Table 7-7 Material Properties for SA-182 Grade F316(t > 5)

Temperature, °F	Sm [ksi]	Sy [ksi]	Su [ksi]
70	20.0	30.0	70.0
100	20.0	30.0	70.0
200	20.0	25.5	70.0
300	20.0	22.9	66.0
400	18.9	21.0	62.6
500	17.5	19.5	60.3
600	16.5	18.3	59.0
650	16.0	17.8	58.6

Table 7-8 Material Properties for SA-182 Grade F304(t ≤ 5)

Temperature, °F	Sm [ksi]	Sy [ksi]	Su [ksi]
70	16.7	25.0	70.0
100	16.7	25.0	70.0
200	16.7	21.4	66.1
300	16.7	19.2	61.2
400	15.8	17.5	58.7
500	14.7	16.4	57.5
600	14.0	15.5	56.9
650	13.7	15.2	56.7

Table 7-9 Material Properties for SA-182 Grade F304(t >5)

Temperature, °F	Sm [ksi]	Sy [ksi]	Su [ksi]
70	16.7	25.0	65.0
100	16.7	25.0	65.0
200	16.7	21.4	61.3
300	16.7	19.2	56.9
400	15.8	17.5	54.5
500	14.7	16.4	53.4
600	14.0	15.5	52.9
650	13.7	15.2	52.6

Table 7-10 Material Properties for SA-540 Grade B24 Class 2

Temperature, °F	Sm [ksi]	Sy [ksi]	Su [ksi]
70	46.7	140.0	155.0
100	46.7	140.0	155.0
200	44.6	134.4	155.0
300	43.1	131.0	155.0
400	41.8	128.7	155.0
500	40.5	126.9	155.0
600	38.7	124.5	155.0
650	37.5	122.7	152.6

Table 7-11 Material Properties for SA-540 Grade B24 Class 4

Temperature, °F	Sm [ksi]	Sy [ksi]	Su [ksi]
70	40.0	120.0	135.0
100	40.0	120.0	135.0
200	38.2	115.2	135.0
300	36.9	112.2	135.0
400	35.9	110.3	135.0
500	34.7	108.8	135.0
600	33.1	106.7	135.0
650	32.1	105.2	132.9

7.3 Loads, Load Combinations, and Transients

The loads, load combinations and transients used in the structural analyses are defined in the RCP ASME Design Specification (Reference 4). Following is a summary of the loads used for the RCP structural evaluations.

7.3.1 Pressure Loads and Temperature

Table 7-12 Pressures and Temperatures

Parameter	Value
Casing Design Pressure	2485 psig
Casing Design Temperature	650^{o}F
Heat Exchanger Design Pressure (External pressure)	2485 psig
Heat Exchanger Design Temperature	650^{o}F
Casing Hydrostatic Test Pressure	[ ]
Casing Minimum Hydrostatic Test Temperature	70^{o}F
No.1 and No.2 Seal Housing Hydrostatic Test Pressure	3107 psig
No.1 and No.2 Seal Housing Minimum Hydrostatic Test Temperature	70^{o}F
Heat Exchanger Inlet & Outlet Nozzle Design Pressure	2485 psig
Heat Exchanger Inlet & Outlet Nozzle Design Temperature	650^{o}F
Heat Exchanger Inlet & Outlet Nozzle Hydrostatic Test Pressure	3107 psig
No.1 and No.2 Seal Housing Minimum Hydrostatic Test Temperature	70^{o}F

7.3.2 External Mechanical Loads

The external loads, obtained from the Design Specification, are dead weight, thermal expansion , seismic I and accident loads. These external loads were applied at the RCP pressure boundary nozzles and supports.

The bolt preload values for the manway, handhole, and inspection port studs were the minimum required bolt loads for the design pressure calculated in accordance with Article E-1000 of the ASME code.

Table 7-13-1 Loads Applied to the Pump Casing Lug #1

Condition	Force lbs			Moment in-lbs		
	Fx	Fy	Fz	Mx	My	Mz
Design						
Level A						
Level B						
Level D Design Load 1						
Level D Design Load 2						

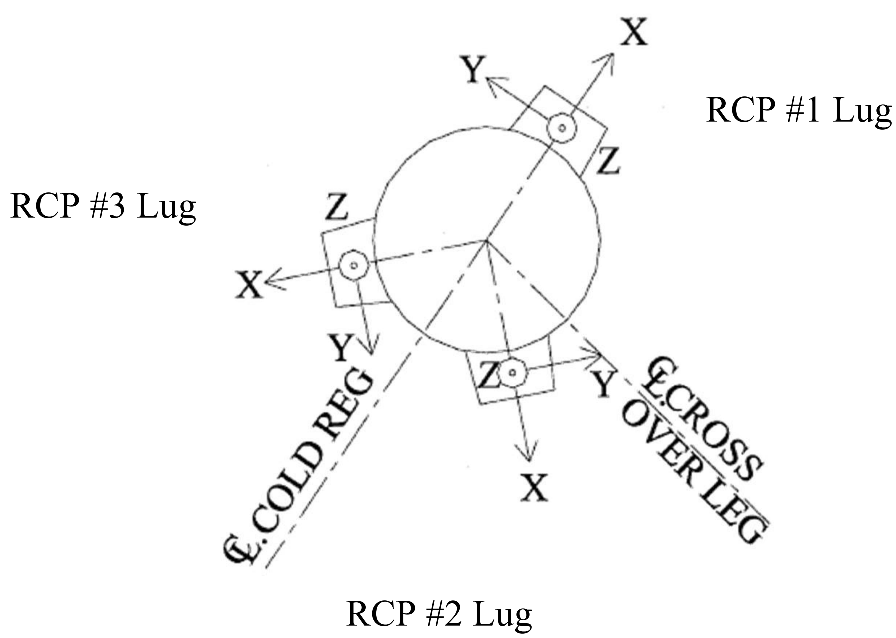


Table 7-13-2 Loads Applied to the Pump Casing Lug #2

Condition	Force lbs			Moment in-lbs		
	Fx	Fy	Fz	Mx	My	Mz
Design						
Level A						
Level B						
Level D Design Load 1						
Level D Design Load 2						

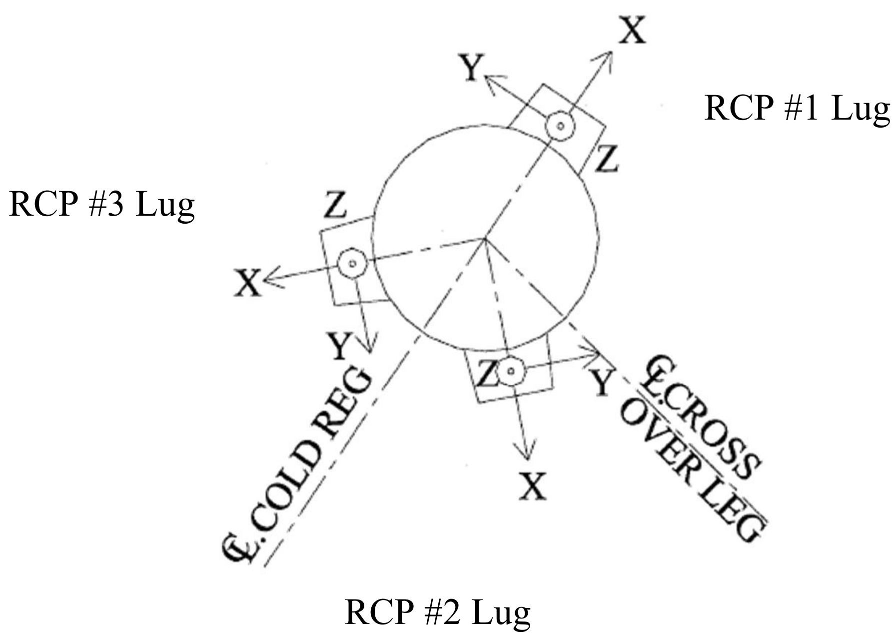


Table 7-13-3 Loads Applied to the Pump Casing Lug #3

Condition	Force lbs			Moment in-lbs		
	Fx	Fy	Fz	Mx	My	Mz
Design						
Level A						
Level B						
Level D Design Load 1						
Level D Design Load 2						

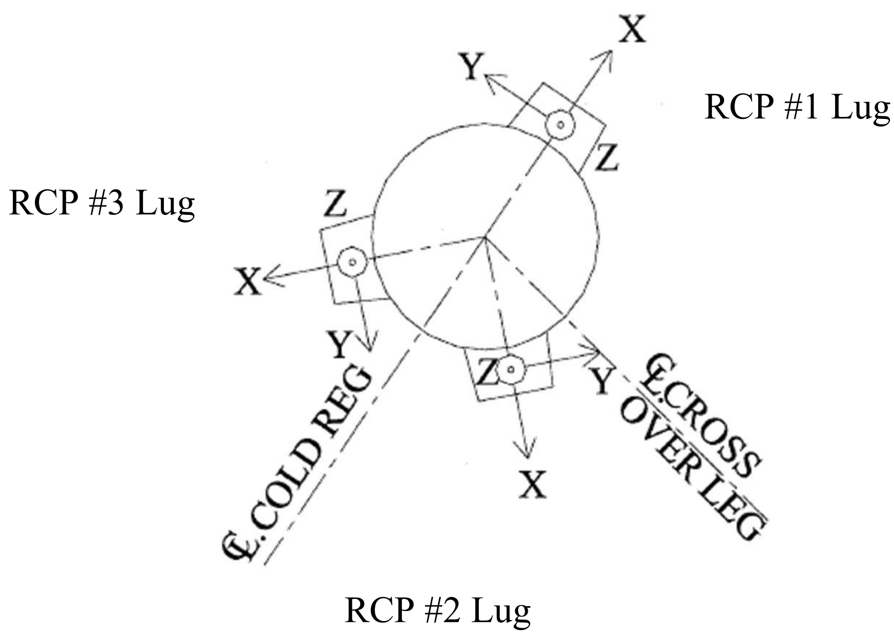
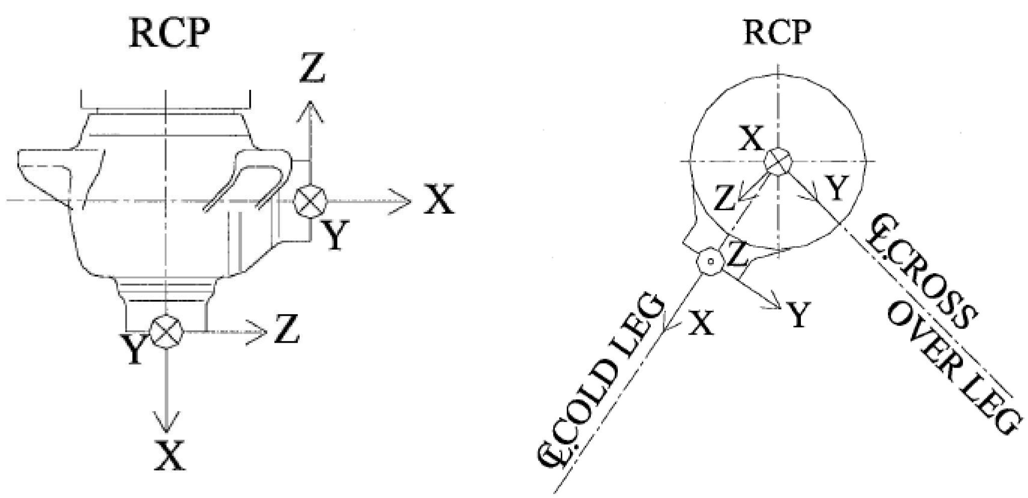


Table 7-14 Loads Applied to the Discharge Nozzle

Condition	Force lbs			Moment in-lbs		
	Fx	Fy	Fz	Mx	My	Mz
Design						
Level A						
Level B						
Level D Design Load 1						
Level D Design Load 2						

RCP Suction Nozzle

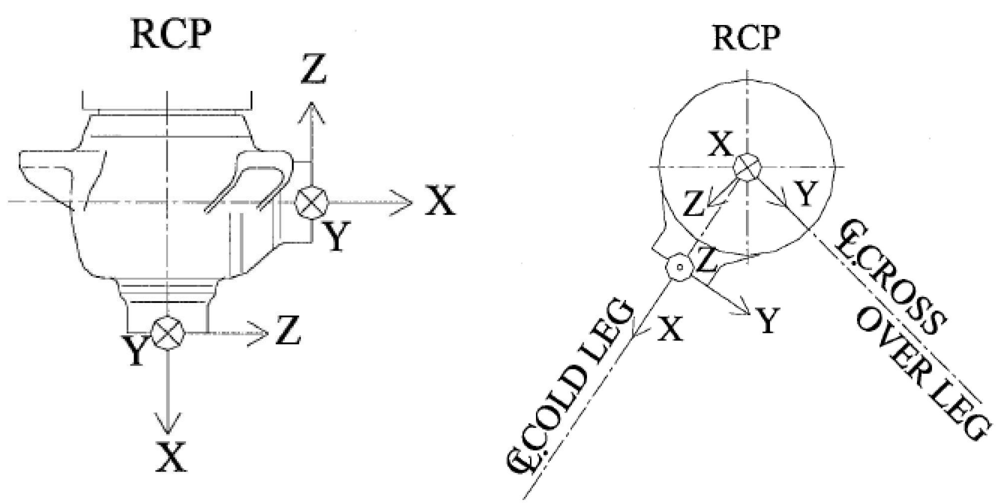


RCP Discharge Nozzle

Table 7-15 Loads Applied to the Suction Nozzle

Condition	Force lbs			Moment in-lbs		
	Fx	Fy	Fz	Mx	My	Mz
Design						
Level A						
Level B						
Level D Design Load 1						
Level D Design Load 2						

RCP Suction Nozzle

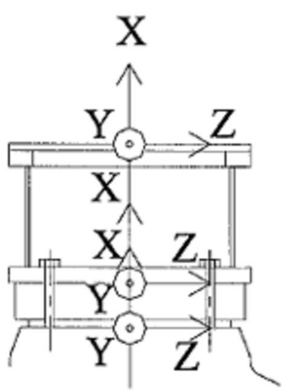


RCP Discharge Nozzle

Table 7-16 Loads Applied to the Lower Motor Stand

Condition	Force lbs			Moment in-lbs		
	Fx	Fy	Fz	Mx	My	Mz
Design						
Level D Design Load 1						
Level D Design Load 2						

RCP Motor Stand Upper



RCP Motor Stand Lower

RCP Casing Bolt

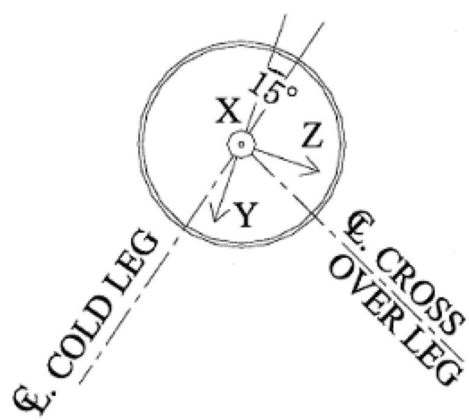
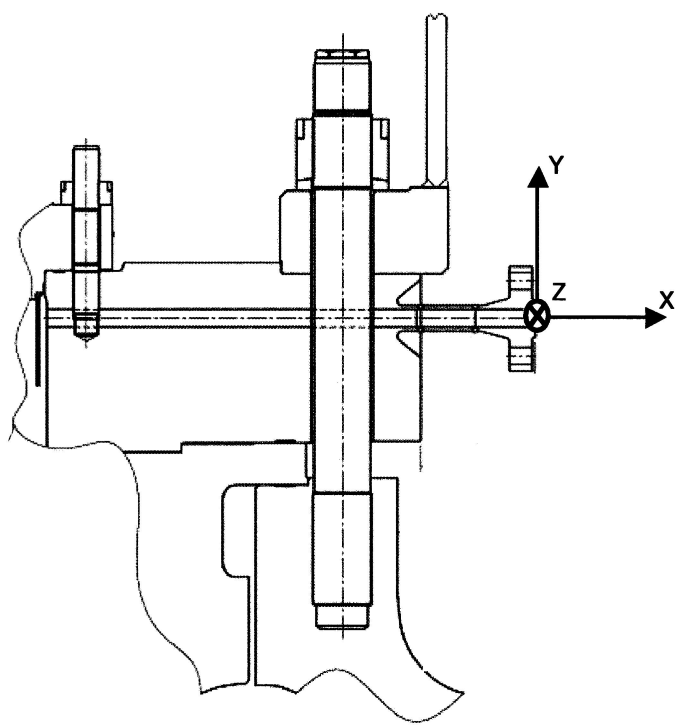


Table 7-17 Loads Applied to the RCP Seal Water Injection Nozzle

Condition	Force lbs			Moment in-lbs		
	Fx	Fy	Fz	Mx	My	Mz
Design						
Level B						
Level D						
TEST						



7.3.3 Thermal and Pressure Transient Loads

The design transients used in the structural evaluations are listed in the Table 7-18. These transients were determined based on a 60-year plant operating period and classified as ASME Level A, Level B, Level C, Level D service conditions, or Test conditions, depending on the expected frequency of occurrence and severity of the event.

Table 7-18 Design Transients

Level A Service Conditions

Mark	Transient	Occurrence	Remark
I-a	Plant heat-up (50F/h)	120	
I-b	Plant cooldown (100F/h)	120	Includes Transient for 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% or full power per minute)	600	
I-c-2	Ramp load increase between 50% and 100% of full power (5% or full power per minute)	19,200	
I-d-1	Ramp load decrease between 15% and 100% of full power (5% or full power per minute)	600	
I-d-2	Ramp load decrease between 50% and 100% of full power (5% or 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 i)	Steady-state fluctuations and load regulation (Steady state fluctuations)	1×10^6	P_P +/- 50psi, T_{hot},T_{cold}, T_{ave}+/- 3.1F
I-h ii)	Steady-state fluctuations and load regulation (Load regulation)	8×10^5	
I-i	Main feedwater cycling	2,100	
I-j	Refueling	60	Water is replaced in 10minutes
I-k	Ramp load increase between 0% and 15% of full power	600	
I-l	Ramp load decrease between 0% and 15% of full power	600	
I-m	RCP startup	3,000	
I-n	RCP shutdown	3,000	
I-o	Core lifetime extension	60	
I-p	Primary leakage test	120	
I-q	Turbine roll test	10	

Level B Service Conditions			
II-a	Loss of load	60	
II-b	Loss of offsite power	60	
II-c	Partial loss of reactor coolant flow	30	
II-d i)	Reactor trip from full power With no inadvertent cooldown	60	
II-d ii)	Reactor trip from full power With cooldown and no safety injection	30	Includes Transient for excessive feedwater flow
II-d iii)	Reactor trip from full power With cooldown and safety injection	10	
II-e	Inadvertent RCS depressurization	30	
II-f	Control rod drop	30	
II-g	Inadvertent safeguards actuation	30	
II-h	Emergency feedwater cycling	700	
II-i	Cold over-pressure	30	
II-j	Excessive feedwater flow	—	Covered by Transient for reactor trip from full power ii)
II-k	Loss of offsite power with natural circulation cooldown	—	Covered by Transient for plant cooldown
II-l	Partial loss of emergency feedwater	30	Use Figure for Transient of loss of offsite power
II-m	Safe Shutdown	—	Covered by Transient for plant cooldown
Level C Service Condition			
III-a	Small loss of coolant accident	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 Service Condition			
IV-a	Large loss of coolant accident	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 Condition			
V-a	Primary-side hydrostatic test	10	

7.3.4 Load Combinations

The loading conditions analyzed consist of various combinations of pressure, temperature and external loads consistent with the Design Specification (Reference 4). The load combinations analyzed are listed in Table 7-19.

The names used for the external loads refer directly to names specified in Table 7-13-1 through 7-17.

Table 7-19 Load Combinations

System Operating Condition and Service Levels		Service Loading Combination
Design	Design	Design Pressure Dead Weight Loads Thermal Loads (note 1) Seismic(1/3 SSE) Loads (note 5)
Normal	Level A	Level A Thermal & Pressure Transients Dead Weight Loads Thermal Loads (note 1)
Upset	Level B	Level B Maximum Pressure (note 2) Level B Thermal & Pressure Transients Dead Weight Loads Thermal Loads (note 1) Seismic(1/3 SSE) Loads
Emergency	Level C	Level C Maximum Pressure Level C Thermal & Pressure Transients(note 3) Dead Weight Loads Thermal Loads (note 1)
Faulted	Level D	Level D Maximum Pressure Dead Weight Loads Thermal Loads (note 1) +/- SRSS(Seismic(SSE) Loads + Accident Loads (note 4))
Test	Test	Dead Weight Loads Hydrostatic Test Pressure

Note 1	Applied to the nozzles within the limits of reinforcement in the primary stress evaluation.(NB-3227.5)
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 Load, each is to be analyzed separately.
Note 5	Design Loads are larger than CDS, so result is conservative.

8.0 METHODOLOGY

The ABAQUS computer program was used to determine mechanical loads, temperature distributions, stresses, and deformations. 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 reactor vessel 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, 7 and 8) 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 in the structure. The RCS fluid temperature versus time curves were applied to all wetted surfaces with appropriate heat transfer coefficients as described, above. The outside surfaces under the vessel insulation were assumed to be 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 in-house proprietary computer programs (CLASS2D, CLASS3D, EDITSTRS, EVALPRI, EVALSEFAV, and RATCHET). These programs are described in Section 9.

Figure 8-1 shows the stress evaluation process.

CLASS2D and CLASS3D classify 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, quantify 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 based on the rules of NB-3216.2 and NB-3222.4(e) of ASME Section III (Reference 1). 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 cases, a fatigue strength reduction factor (FSRF) was used where the peak stress could not be accurately calculated. In these cases, the factor was applied to the surface stress produced by a linear stress distribution (through the wall thickness) that produced the identical displacement / rotation of the section (i.e. equivalent structural equilibrium).

The design transients for ASME Level A and B service conditions (Table 7-19) were used in the evaluation of cyclic fatigue. The effect of 300 cycles of a 1/3 SSE seismic event was also included in the evaluation of cyclic 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 for a single SSE event of 20 cycles.

9.0 COMPUTER PROGRAMS USED

Refer to Figure 8-1 for a visual description of the Stress Evaluation Process. Table 9-1 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	3.0	CLASS2D is an MHI code for classifying the stresses for axisymmetric models
3	CLASS3D	3.0	CLASS3D is an MHI code for classifying the stresses for 3D solid models
4	EDITSTRS	3.0	EDITSTRS is an MHI code that creates input files for the stress evaluation programs
5	EVALPRI	5.0	EVALPRI is an MHI code that performs the primary stress evaluation
6	EVALSEFAV	4.0	EVALSEFAV is an MHI code that performs the secondary stress and fatigue evaluation
7	RATCHET	5.0	RATCHET is an MHI code that evaluates thermal stress ratcheting
8	ASMETEMP	0.0	ASMETEMP is an MHI code that creates temperature files for the stress evaluation program

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 eight parts of the RCP that were analyzed. Dimensional drawings, illustrations of the finite element models or descriptions of hand calculations, and summaries of the stress and fatigue analysis results are presented for each of the eight parts of the RCP. The results of the stress and fatigue analyses presented are generally conservative. It is expected that the resulting stress values and fatigue usage factors would be lower if more detailed calculations were performed; but since the results of the analyses all meet the ASME Code allowable limits, further analysis is not necessary.

10.1 Pump Casing Lugs

10.1.1 Pump Casing Lugs Modeling and Analysis

Figure 10.1-1 Pump Casing Lug Dimensions

Figure 10.1-2 Pump Casing Lug Finite Element Model

10.1.2 Pump Casing Lugs Stress Results

The calculated stresses and corresponding allowable values, the cumulative fatigue usage factors, and the thermal stress ratchet results for the most limiting locations of the RCP casing lugs are summarized in Tables 10.1-1 through 10.1-5.

Table 10-1-1 Summary of Primary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio	
		Pm	Pm+Pb
Design	No.1 Lug		
	No.2 Lug		
	No.3 Lug		
Level D	No.1 Lug		
	No.2 Lug		
	No.3 Lug		
Test	No.1 Lug		
	No.2 Lug		
	No.3 Lug		

Table 10-1-2 Summary of Primary plus Secondary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Pm+Pb+Q
Level A/B	No.1 Lug	
	No.2 Lug	
	No.3 Lug	

Table 10-1-3 Summary of Fatigue evaluations

Condition	Part	Usage Factor
Level A/B	No.1 Lug	
	No.2 Lug	
	No.3 Lug	

Table 10-1-4 Summary of Triaxial Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Triaxial Stress
Design	No.1 Lug	
	No.2 Lug	
	No.3 Lug	
Test	No.1 Lug	
	No.2 Lug	
	No.3 Lug	

Table 10-1-5 Summary of Thermal Ratchet evaluations

Condition	Part	Stress-to-Allowable Ratio
		Thermal Stress
Level A	No.1 Lug	
	No.2 Lug	
	No.3 Lug	

10.2 Discharge Nozzle

10.2.1 Discharge Nozzle Modeling and Analysis Dimensions

Figure 10.2-1 Discharge Nozzle Dimensions

Figure 10.2-2 Discharge Nozzle Finite Element Model

10.2.2 Discharge Nozzle Stress Results

The calculated stresses and corresponding allowable values, the cumulative fatigue usage factors, and the thermal stress ratchet results for the most limiting locations in the RCP discharge nozzle are summarized in Tables 10.2-1 through 10.2-5.

Table 10-2-1 Summary of Primary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio	
		Pm	Pm+Pb
Design	Nozzle End		
	Nozzle Body		
	Nozzle to Shell Junction		
Level D	Nozzle End		
	Nozzle Body		
	Nozzle to Shell Junction		
Test	Nozzle End		
	Nozzle Body		
	Nozzle to Shell Junction		

Table 10-2-2 Summary of Primary plus Secondary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Pm+Pb+Q
Level A/B	Nozzle End	
	Nozzle Body	
	Nozzle to Shell Junction	

Table 10-2-3 Summary of Fatigue evaluations

Condition	Part	Usage Factor
Level A/B	Nozzle End	
	Nozzle Body	
	Nozzle to Shell Junction	

Table 10-2-4 Summary of Triaxial Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Triaxial Stress
Design	Nozzle End	
	Nozzle Body	
	Nozzle to Shell Junction	
Test	Nozzle End	
	Nozzle Body	
	Nozzle to Shell Junction	

Table 10-2-5 Summary of Thermal Ratchet evaluations

Condition	Part	Stress-to-Allowable Ratio
		Thermal Stress
Level A	---	

10.3 Suction Nozzle

10.3.1 Suction Nozzle Modeling and Analysis

Figure 10.3-1 Suction Nozzle Dimensions

Figure 10.3-2 Suction Nozzle Finite Element Model

10.3.2 Suction Nozzle Stress Results

The calculated stresses and corresponding allowable values, the cumulative fatigue usage factors, and the thermal stress ratchet results for the most limiting locations in the RCP suction nozzle are summarized in Tables 10.3-1 through 10.3-5.

Table 10-3-1 Summary of Primary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio	
		Pm	Pm+Pb
Design	Nozzle End		
	Nozzle Body		
	Nozzle to Shell Junction		
Level D	Nozzle End		
	Nozzle Body		
	Nozzle to Shell Junction		
Test	Nozzle End		
	Nozzle Body		
	Nozzle to Shell Junction		

Table 10-3-2 Summary of Primary plus Secondary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Pm+Pb+Q
Level A/B	Nozzle End	
	Nozzle Body	
	Nozzle to Shell Junction	

Table 10-3-3 Summary of Fatigue evaluations

Condition	Part	Usage Factor
Level A/B	Nozzle End	
	Nozzle Body	
	Nozzle to Shell Junction	

Table 10-3-4 Summary of Triaxial Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Triaxial Stress
Design	Nozzle End	
	Nozzle Body	
	Nozzle to Shell Junction	
Test	Nozzle End	
	Nozzle Body	
	Nozzle to Shell Junction	

Table 10-3-5 Summary of Thermal Ratchet evaluations

Condition	Part	Stress-to-Allowable Ratio
		Thermal Stress
Level A	---	

10.4 Main Flange and Studs

10.4.1 Main Flange and Studs Modeling and Analysis

Figure 10.4-1 Main Flange & Stud Dimensions

Figure 10.4-2 Main Flange & Stud Finite Element Model

10.4.2 Main Flange and Studs Stress Results

The calculated stresses and corresponding allowable values, the cumulative fatigue usage factors, and the thermal stress ratchet results for the most limiting locations in the RCP main flange and studs are summarized in Tables 10.4-1 through 10.4-6.

Table 10-4-1 Summary of Primary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio	
		Pm	Pm+Pb
Design	Flange (Upper)		
	Flange (Lower)		
	Stud Bolt		
Level D	Flange (Upper)		
	Flange (Lower)		
	Stud Bolt		
Test	Flange (Upper)		
	Flange (Lower)		
	Stud Bolt		

Table 10-4-2 Summary of Primary plus Secondary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Pm+Pb+Q
Level A/B	Flange (Upper)	
	Flange (Lower)	

Table 10-4-3 Summary of Fatigue evaluations

Condition	Part	Usage Factor
Level A/B	Flange (Upper)	
	Flange (Lower)	
	Stud Bolt	

Table 10-4-4 Summary of Triaxial Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Triaxial Stress
Design	Flange (Upper)	
	Flange (Lower)	
Test	Flange (Upper)	
	Flange (Lower)	

Table 10-4-5 Summary of Thermal Ratchet evaluations

Condition	Part	Stress-to-Allowable Ratio
		Thermal Stress
Level A	Flange (Upper)	
	Flange (Lower)	

Table 10-4-6 Summary of Bearing Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Triaxial Stress
Design	Flange (Upper)	
Level A	Flange (Upper)	
Level B	Flange (Upper)	
Test	Flange (Upper)	

10.5 No.1 and 2 Seal Housings

10.5.1 Seal Housings and Studs Modeling and Analysis

Figure 10.5-1 Seal Housing Dimensions

Figure 10.5-2 Seal Housing Finite Element Model

10.5.2 Seal Housings and Studs Stress Results

The loadings on the No. 1 seal housing are significantly larger than those of the other seal housings, so only the results from seal housing No. 1 are reported.

Table 10-5-1 Summary of Primary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio	
		Pm	Pm+Pb
Design	No.1 Seal Housing		
	Stud Bolt		
Level D	No.1 Seal Housing		
	Stud Bolt		
Test	No.1 Seal Housing		
	Stud Bolt		

Table 10-5-2 Summary of Primary plus Secondary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Pm+Pb+Q
Level A/B	No.1 Seal Housing	

Table 10-5-3 Summary of Fatigue evaluations

Condition	Part	Usage Factor
Level A/B	No.1 Seal Housing	
	Stud Bolt	

Table 10-5-4 Summary of Triaxial Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Triaxial Stress
Design	No.1 Seal Housing	
Test	No.1 Seal Housing	

Table 10-5-5 Summary of Bearing Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Triaxial Stress
Design	No.1 Seal Housing	
Level A	No.1 Seal Housing	
Level B	No.1 Seal Housing	
Test	No.1 Seal Housing	

Table 10-5-6 Summary of Thermal Ratchet evaluations

Condition	Part	Stress-to-Allowable Ratio
		Thermal Stress
Level A	No.1 Seal Housing	

10.6 Diffuser Flange

10.6.1 Diffuser Flange Modeling and Analysis

Figure 10.6-1 Diffuser Flange Dimensions

Figure 10.6-2 Diffuser Flange Finite Element Model

10.6.2 Diffuser Flange Stress Results

The calculated stresses and corresponding allowable values, the cumulative fatigue usage factor, and the thermal stress ratchet results for the most limiting locations in the RCP diffuser flange are summarized in Tables 10.6-1 through 10.6-6, below.

Table 10-6-1 Summary of Primary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio	
		Pm	Pm+Pb
Design	Diffuser Flange		
Level D	Diffuser Flange		
Test	Diffuser Flange		

Table 10-6-2 Summary of Primary plus Secondary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Pm+Pb+Q
Level A/B	Diffuser Flange	

Table 10-6-3 Summary of Fatigue evaluations

Condition	Part	Usage Factor
Level A/B	Diffuser Flange	

Table 10-6-4 Summary of Triaxial Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Triaxial Stress
Design	Diffuser Flange	
Test	Diffuser Flange	

Table 10-6-5 Summary of Bearing Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Triaxial Stress
Design	Diffuser Flange	
Level A	Diffuser Flange	
Level B	Diffuser Flange	
Test	Diffuser Flange	

Note: Actual is 0.998 and bearing stress is less than allowable stress.

Table 10-6-6 Summary of Thermal Ratchet evaluations

Condition	Part	Stress-to-Allowable Ratio
		Thermal Stress
Level A	Diffuser Flange	

10.7 Heat Exchanger Tubing

10.7.1 Heat Exchanger Tubing Modeling and Analysis

Figure 10.7-1 Heat Exchanger Tube Dimensions

The heat exchanger tube stresses were calculated by hand using Classical structural mechanics equations. The analysis includes and evaluation of tube collapse under the hydrostatic test external pressure.

10.7.2 Heat Exchanger Tubing Stress Results

The calculated stress and corresponding allowable values and the cumulative fatigue usage factor for the most limiting locations in the RCP thermal barrier heat exchanger are summarized in Tables 10.7-1 through 10.7-6.

Table 10-7-1 Summary of Primary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio	
		Pm	Pm+Pb
Design	Tube free length Tube butt weld (mid-span) Tube-to-header weld		
Level A/B	Cooling Coil		
Test	Cooling Coil		

Table 10-7-2 Summary of Primary plus Secondary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Pm+Pb+Q
Level A/B	Cooling Coil	[ ]

Table 10-7-3 Summary of Fatigue evaluations

Condition	Part	Usage Factor
Level A/B	Cooling Coil	[ ]

Table 10-7-4 Summary of Triaxial Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Triaxial Stress
Level A/B	Cooling Coil	[
Test	Cooling Coil	]

Note: Triaxial Stress is lower than zero.

Table 10-7-5 Summary of Primary plus Secondary Stress evaluations for hydrostatic testing condition of Cooling Coil-Internal Pressure

Condition	Part	Stress-to-Allowable Ratio
		Pm+Pb
Test	Cooling Coil	[ ]

Table 10-7-6 Summary of Triaxial Stress evaluations for hydrostatic testing condition of Cooling Coil-Internal Pressure

Condition	Part	Stress-to-Allowable Ratio
		Triaxial Stress
Test	Cooling Coil	[ ]

10.8 RCP Seal Water Injection Nozzle

10.8.1 Seal Water Injection Nozzle Modeling and Analysis

Figure 10.8-1 RCP Seal Water Injection Nozzle Dimensions

Finite Element Model is not applied to stress analysis of the RCP Seal Water Injection Nozzle. Hand calculation is applied.

10.8.2 Seal Water Injection Nozzle Stress Results

The calculated stresses and corresponding allowable values for the most limiting locations in the seal water injection nozzle are summarized in the Tables 10.8-1, below.

Table 10-8-1 Summary of Primary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio	
		Pm [ksi]	Pm+Pb [ksi]
Design	Nozzle End		
	Nozzle Body		
	Nozzle-to-Shell Junction		
Level D	Nozzle End		
	Nozzle Body		
	Nozzle-to-Shell Junction		
TEST	Nozzle End		
	Nozzle Body		
	Nozzle-to-Shell Junction		

Table 10-8-2 Summary of Fatigue evaluations

Condition	Part	Usage Factor
Level B	Nozzle End	
	Nozzle Body	
	Nozzle-to-Shell Junction	

11.0 REFERENCES

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