Summary of Stress Analysis Results for the US-APWR Control Rod Drive Mechanism

Non-Proprietary Version

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Revision History

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Abstract

This report contains a summary of the structural evaluations of the two Control Rod Drive Mechanism parts.

The calculations are based on the loading conditions defined in the US-APWR Control Rod Drive Mechanism Design Specification (Reference 4) and on the procedures per ASME Boiler & Pressure Vessel Code Section III (Reference 1).

All of the stress intensity limits specified in the 2001 Edition of Section III of the ASME Boiler & Pressure Vessel Code up to and including the 2003 addenda are satisfied.

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List of Acronyms

The following list defines the acronyms used in this document.

CRDM	Control Rod Drive Mechanism
SSE	Safe Shutdown Earthquake
FSRF	Fatigue Strength Reduction Factor
LOCA	Loss-of-Coolant Accident
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RVCH	Reactor Vessel Closure Head
FEA	Finite Element Analysis
FEM	Finite Element Model
RCCA	Rod Cluster Control Assembly

1.0 INTRODUCTION

This report provides details of the stress analysis results for the US-APWR Control Rod Drive Mechanism (CRDM). The first part of this document provides summary, and its detail is provided in Appendix. The content of this report follows the ASME guidelines for Design Reports (ASME Code Section III Division 1 Appendix C) (Reference 1).

The CRDM is a vertical cylindrical vessel with hemispherical top head. The CRDM is welded to the CRDM nozzle on the Reactor Vessel Closure Head (RVCH). Figure 1-1 shows the general configuration of the US-APWR CRDM.

This report summarizes the results and conclusions based upon detailed analyses that demonstrate the validity of the CRDM components to meet the requirements of the Design Specification (Reference 4).

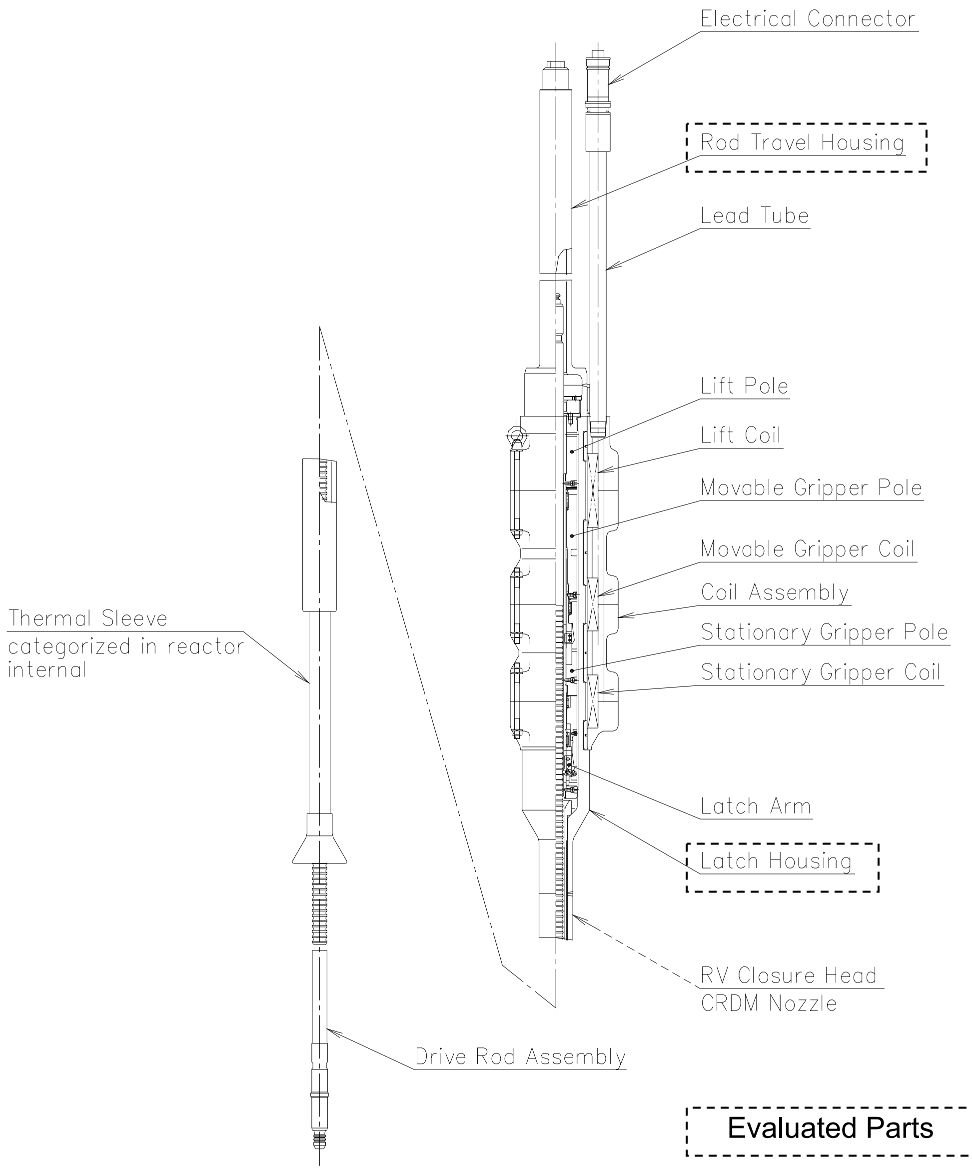


Figure 1-1 General Configuration of the US-APWR Control Rod Drive Mechanism

2.0 SUMMARY OF RESULTS

The evaluated part of the CRDM along with the most limiting result, is listed in Table 2-1 below. The structural analysis results for the part are provided in Section 10.

Table 2-1 Summary of Most Limiting Results

Section	Evaluated Part	Max Stress / Allowable Ratio[1]	Highest Fatigue Usage Factor[2]
10.1	Pressure Housing (Latch Housing and Rod Travel Housing)	[	]

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 of Reference. Environmental fatigue per RG 1.207 will be evaluated separately.

3.0 CONCLUSIONS

The US-APWR CRDM was 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 summarized in this report and a review of the component design drawings, it is concluded that the US-APWR CRDM 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 Strength
S_u	ksi	Tensile Strength
Y_A	-	Thermal Ratcheting Factor
SS	ksi	Thermal Stress Range
α	-	Shape Factor
σ_S	ksi	Thermal ratchet stress

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.

5.2 OPEN ITEMS

There are no open items in this report.

6.0 ACCEPTANCE CRITERIA

The stress intensity acceptance criteria for the Class 1 components are specified in the NB-3220 and Appendix F of ASME Code Section III. Table 6-1 lists the stress limits (other than 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
	$P_L + P_b$	α (1.1S_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 (α (1.2 S_m), α 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 α S_y for non-rectangular sections) (2.15 S_y -1.2 P_m) - for 0.67 $S_y < P_m \leq 0.9\ S_y$	
	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.

7.0 DESIGN INPUT

7.1 GEOMETRY

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

Table 7-1 US-APWR CRDM Basic Design Drawing List

No.	Drawing Title	Drawing Number
1	Control Rod Drive Mechanism Design Drawings	N0-EC50101

7.2 MATERIAL

The materials for the CRDM pressure housing is listed in Table 7-2 below.

Table 7-2 Materials of Construction

Part or Assembly	Material
Rod Travel Housing	SA-182 Grade F316
Latch Housing	SA-182 Grade F316

The material strength properties used in the stress analyses are obtained from ASME Section II (Reference 2).

Table 7-3 Material Properties for (SA-182 Grade F316)

Temperature(°F)	S_m (ksi)	S_y (ksi)	S_u (ksi)
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

7.3 LOADS, LOAD COMBINATIONS, AND TRANSIENTS

The loads, load combinations and transients are defined in the CRDM Design Specification (Reference 4). The following is a summary of those used for the CRDM structural evaluations.

7.3.1 Pressure Loads and Temperature

Table 7-4 Pressures and Temperatures for each Service Level

ASME Service Level	Pressure(1) (psig)	Temperature(°F)
Design		
Level A		
Level B		
Level C		
Level D		
Test		

Note-1: The pressure values are enveloped value that will be used for the CRDM stress analysis for each service level.

7.3.2 External Mechanical Loads

The external loads are dead weights, seismic loads and accident loads. The external loads were considered at the thread sleeve and pressure boundary and were obtained from the CRDM Design Specification (Reference 4).

Figure 7-1 shows the locations of the CRDM where the loads are applied. The Tables 7-5 and 7-6 below provide information concerning the local coordinate systems, loads and loading combinations.

Table 7-5 Loads application for the Rod Travel Housing

ASME Service Level	Local Coordinate System	External Loads	Load Combination
Design	Figure 7-2	Table 7-4	Table 7-11
Level A		Table 7-4 Table 7-10	
Level B		Table 7-4 Table 7-8 Table 7-10 (Figure 7-3)	
Level C		Table 7-4	
Level D		Table 7-4 Table 7-9 (Figure 7-4)	
Test		Table 7-4	

Note:1: The dead weight of the pressure housing will be considered as the density of the metal and added dead weight of the internal water

Table 7-6 Loads application for the Latch Housing

ASME Service Level	Local Coordinate System	External Loads	Load Combination
Design	Figure 7-1	Table 7-4 Table 7-7	Table 7-11
Level A		Table 7-4 Table 7-7 Table 7-10	
Level B		Table 7-4 Table 7-7 Table 7-8 Table 7-10 (Figure 7-3)	
Level C		Table 7-4 Table 7-7	
Level D		Table 7-4 Table 7-7 Table 7-9 (Figure 7-4)	
Test		Table 7-4 Table 7-7	

Note: 1: The dead weight of the pressure housing will be considered as the density of the metal and added dead weight of the internal water

Table 7-7 Mechanical Loads for the CRDM Latch Housing

No.	Loading	Location	Load	Reference
1	Dead Weight (lbf)	Latch Housing top (Rod Travel Housing)		
		Latch assembly Drive Rod Assembly RCCA Thread Sleeve Retaining Key		
		Rod Position Indicator Upper Spacer Plate		
		Flux Ring 1		
		Flux Ring 2		
		Flux Ring 3		
		Flux Ring 4		
		Coil Stack Assembly Ventilation Dummy CRDM Middle Seismic Plate Assembly		
		Thermal Sleeve		
2	Mechanical Load (ksi)	Pre-Loads of Thread Sleeve		
		Latch Housing Shoulder		

Note:1: Mechanical loads are applied as pressure loading. The mechanical load is divided by projected area of the loading surface.

Table 7-8 Loads of the CRDM for Level B (1/3 SSE)

Table 7-9 Loads of the CRDM for Level D (SSE+LOCA)

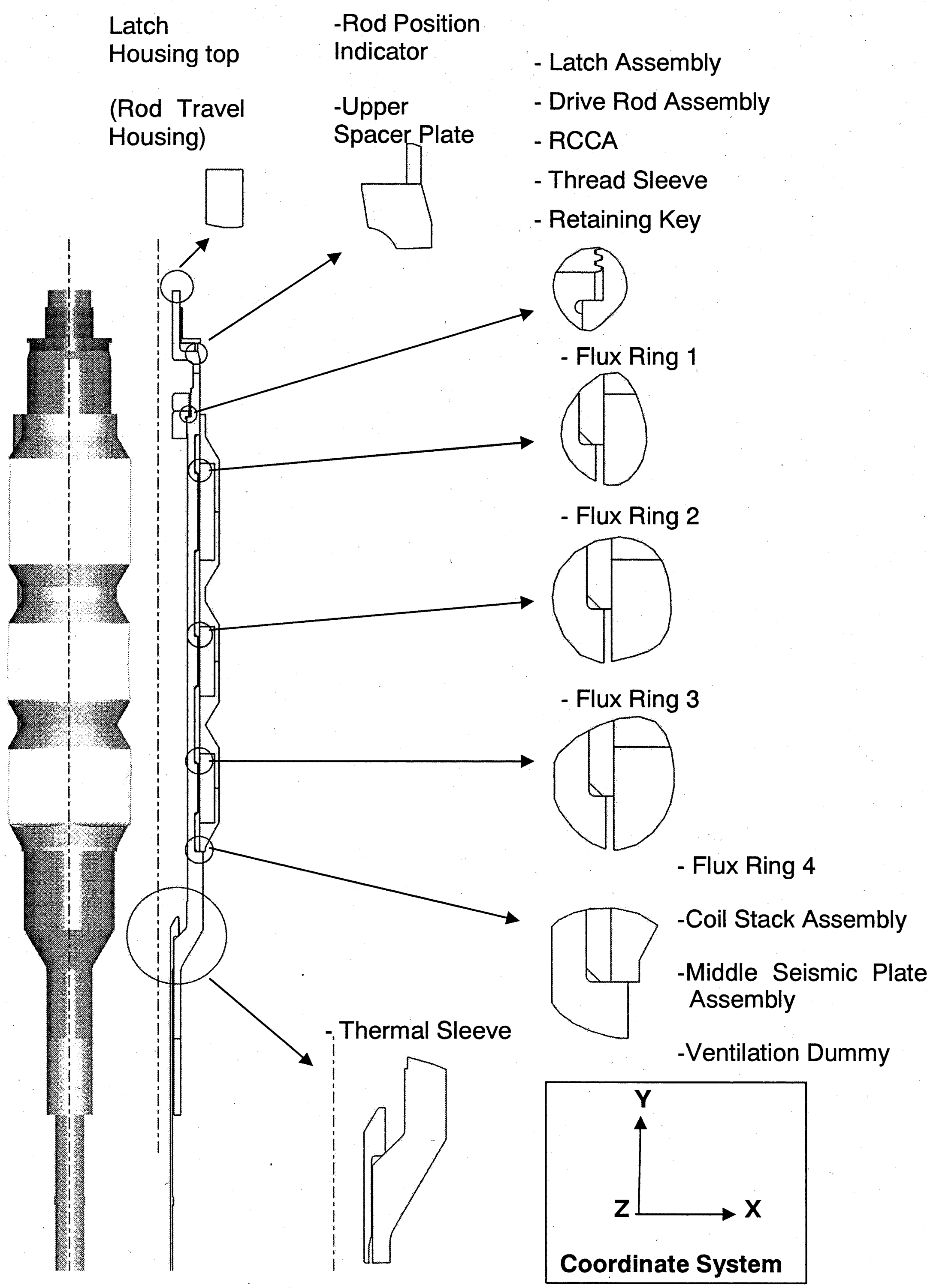
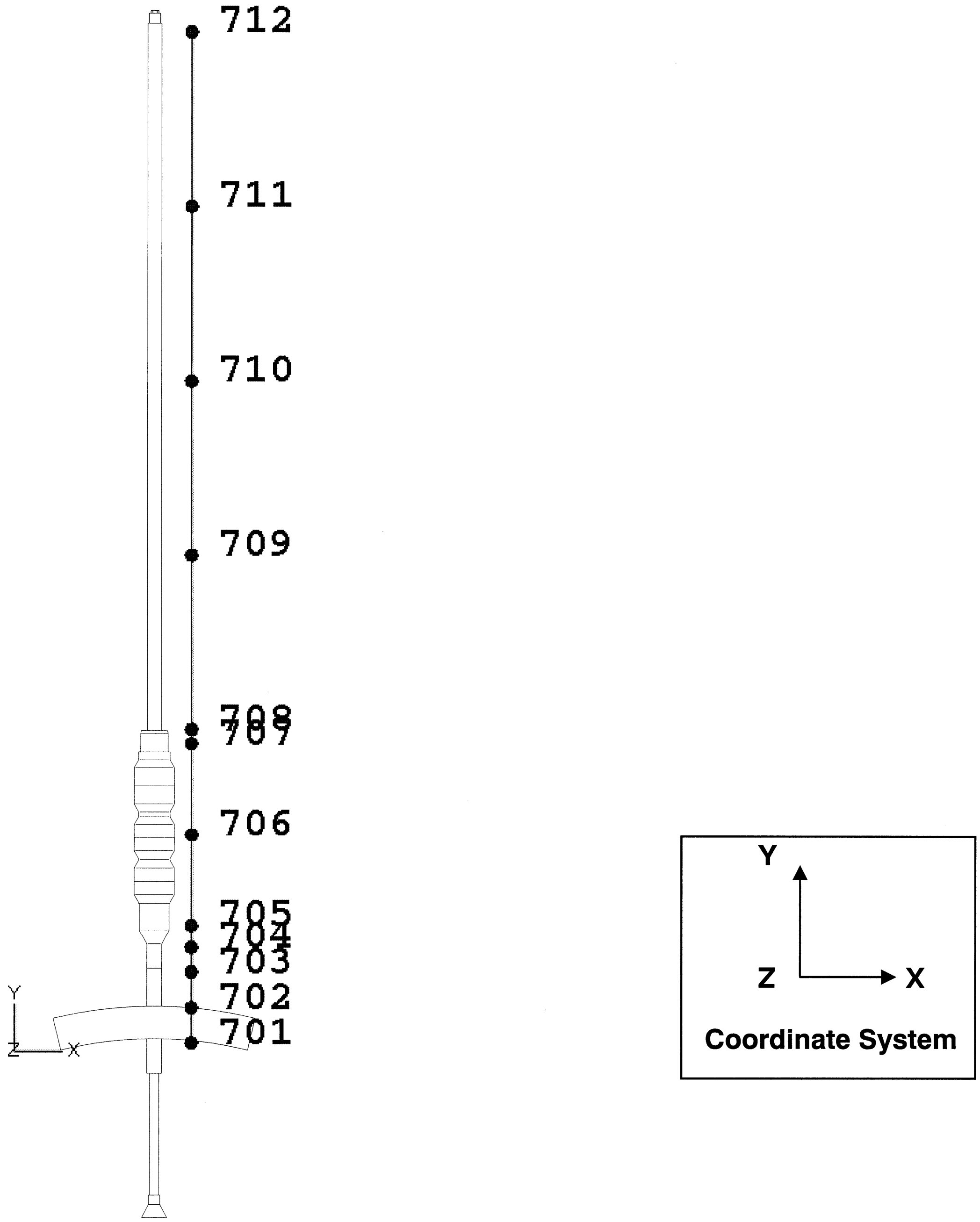


Figure 7-1 Locations of Loading for the CRDM Mechanical Loads



Note: Reference point of the elevation is the reactor vessel inlet nozzle center

Figure 7-2 Loading Coordinate System for the CRDM Assembly

Figure 7-3(1/3) Axial Force of the CRDM for Level B (1/3 SSE)

Figure 7-3(2/3) Shear Forces of the CRDM for Level B (1/3 SSE)

Figure 7-3(3/3) Bending Moments of the CRDM for Level B (1/3 SSE)

Figure 7-4(1/3) Axial Force of the CRDM for Level D (SSE+LOCA)

Figure 7-4(2/3) Shear Force of the CRDM for Level D (SSE+LOCA)

Figure 7-4(3/3) Bending Moment of the CRDM for Level D (SSE+LOCA)

7.3.3 Thermal and Pressure Transient Loads

The design transients are listed in Table 7-10 below. 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. [In addition, the thermal transient was developed conservatively as was the effect of the drive rod movement, resulting in predicted higher stresses.]

Table 7-10 CRDM Design Transients

Event	Cycles
Level A Service Conditions	
Plant heat-up (50F/h)	120
Plant cooldown (100F/h)	120
Ramp load increase between 15% and 100% of full power (5% or full power per minute)	600
Ramp load increase between 50% and 100% of full power (5% or full power per minute)	19,200
Ramp load decrease between 15% and 100% of full power (5% or full power per minute)	600
Ramp load decrease between 50% and 100% of full power (5% or full power per minute)	19,200
Step load increase of 10% of full power	600
Step load decrease of 10% of full power	600
Large step load decrease with turbine bypass	60
Steady-state fluctuations and load regulation i) Steady state fluctuations	1×10^6
ii) Load regulation	8×10^5
Main feedwater cycling	2,100
Refueling	60 (Not applicable)
Ramp load increase between 0% and 15% of full power	600
Ramp load decrease between 0% and 15% of full power	600
RCP startup	3,000
RCP shutdown	3,000
Core lifetime extension	60
Primary leakage test	120
Turbine roll test	10
Level B Service Conditions	
1/3 SSE (15 events, 20 cycles each)	300
Loss of load	60
Loss of offsite power	60
Partial loss of reactor coolant flow	30
Reactor trip from full power i) With no inadvertent cooldown	60
ii) With cooldown and no safety injection	30
iii) With cooldown and safety injection	10
Inadvertent RCS depressurization	30
Control rod drop	30
Inadvertent safeguards actuation	30
Emergency feedwater cycling	700

Table 7-10 CRDM Design Transients

Event	Cycles
Cold over-pressure	30
Excessive feedwater flow	—
Loss of offsite power with natural circulation cooldown	—
Partial loss of emergency feedwater	30
Safe shutdown	—
Level C Service Conditions	
Small loss of coolant accident	5
Small steam line break	5
Complete loss of flow	5
Small feedwater line break	5
SG tube rupture	5
Level D Service Conditions	
Large loss of coolant accident	1
Large steam line break	1
RCP locked rotor	1
Control rod ejection	1
Large feedwater line break	1
Test Conditions	
Primary-side hydrostatic test	10

7.3.4 Load Combinations

The loading conditions consist of the various combinations of pressure, temperature and external loads. The loads combinations considered in the analysis are listed in Table 7-11 below.

Table 7-11 Load Combinations for the CRDM Stress Analysis

System Operating Condition	ASME Service Level	Service Loading Combination
Design	Design	Design Pressure (2485 psig) Dead weight External Mechanically Applied Loads*1
Normal	Level A	Full power operating pressure or Transient Dead weight External Mechanically Applied Loads*1 Level A thermal & pressure transients including thermal expansion loads
Upset	Level B	Maximum operating pressure Dead weight External Mechanical Applied Loads*1 Level B thermal & pressure transients including thermal expansion loads 1/3 SSE Loads
Emergency	Level C	Maximum operating pressure Dead weight External Mechanically Applied Loads*1
Faulted	Level D	Maximum operating pressure Dead weight External Mechanically Applied Loads *1 SRSS (SSE+ Accident)
Test	Test	Hydrostatic test pressure Dead weight External Mechanically Applied Loads *1

Note:

*1: Mechanical load and weight due to the clamping load of thread sleeve, weight of the latch housing, drive rod assembly, RCCA, retaining key.

8.0 METHODOLOGY

The ABAQUS computer program was used to determine the 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. A description of ABAQUS is available in the public domain. The code has been used by MHI for the U.S. replacement steam generator and replacement RVCH 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 the transients. Classical Handbook heat transfer equations (References 6 and 7) 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 wetted surfaces with the appropriate heat transfer coefficients with consideration of the effect of the drive rod movements. The outside surfaces under the vessel insulation were considered adiabatic.

8.2 STRESS ANALYSIS

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

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

The stress due to external load was derived by the hand calculation.

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

Figure 8-1 Stress Evaluation Process for CRDM

8.3 FATIGUE ANALYSIS MODEL AND METHOD

The fatigue analysis was conducted using the standard rules of NB-3216.2 and NB-3222.4(e) of ASME Code 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 cases, such as the welded joints, a fatigue strength reduction factor (FSRF) was used where the peak stress cannot be accurately calculated. In these cases, the factor is applied to the membrane plus bending stress.

The design transients for ASME Level A and B service conditions (Table 7-10) were used in the evaluation of fatigue caused by cyclic fatigue. The effect of 300 cycles of a 1/3 SSE seismic event was also included in the evaluation of fatigue, treated as the 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.

9.0 COMPUTER PROGRAMS USED

Refer to Figure 8-1 for a visual description of the Stress Evaluation Process. The Table 9-1 below provides a brief description of each of the computer programs used.

10.0 STRUCTURAL ANALYSIS RESULTS

The stress calculations were carried out by a combination of finite element analysis (FEA) and the hand calculations.

The critical sections, for each part of CRDM were evaluated in accordance with the ASME Code Section III criteria, which are presented in Section 6.0.

The calculated results were conservative compared to the values that would be determined if more detailed calculations were performed. However, since the ASME Code allowable limits were satisfied in all cases, further analysis was not necessary.

10.1 PRESSURE HOUSING

10.1.1 MODELING AND ANALYSIS

Figure 10-1 through 10-3 show dimension of the analysis models. For more realistic thermal analysis, a two-dimensional finite element model with latch assembly, thread sleeve, flux ring, and coil assembly was developed in addition to a model for structural analysis.

Figure 10-4 through 10-6 show finite element models.

Figure 10-7 and 10-8 show evaluated parts for CRDM.

Figure 10-1 Upper Model Dimensions

Figure 10-2 Lower Model Dimensions

Figure 10-3 Lower Thermal Model Dimensions

Figure 10-4 Finite Element Model of Upper Model

Figure 10-5 Finite Element Model of Lower Model

Figure 10-6 Finite Element Model of Lower Thermal Model

Figure 10-7 Evaluated part for Upper Model

Figure 10-8 Evaluated parts for Lower Model

10.1.2 Stress Results

Figure 10-7 and 10-8 above show the evaluated parts for Pressure Housing.

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

Table 10-1 Pressure Housing Result Summary

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

11.0 REFERENCES

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