# Summary of Stress Analysis Results for the US-APWR Reactor Coolant Loop Piping

Non-proprietary Version

February 2011

# Revision History

| Revision | Page | Description |
|---|---|---|
| 0 | All | Original Issue |
| 1 | i & ii | Add the sections and change the page numbers. |
| | iii | Add the tables and change the page numbers. |
| | iv | Add the figures and change the page numbers. |
| | v | Add the acronyms. |
| | 1-1 | Change Figure 1-1. |
| | 2-1 | Change Table 2-1. |
| | 4-1 | Add the nomenclatures in Table 4-1. |
| | 6-1 | Add the sentences. |
| | 6-2 | Add “according to NB-3600” to the title of Table 6-1. |
| | 6-3 | Add Table 6-2. |
| | 7-2 | Add the material of nozzles in Table 7-2. |
| | 7-2 | Add the values of $S_u$ in Table 7-3. |
| | 7-3 | Change the table numbers and add the sentences. |
| | 7-4 | Change the figure number. |
| | 7-5 | Add Figure 7-1-2. |
| | 7-6 to 7-10 | Change the table numbers. |
| | 7-11 to 7-13 | Add Tables 7-5-4 to 7-5-9 |
| | 7-14 | Change the 1st paragraph. |
| | 7-14 & 7-15 | Change the table number. |
| | 7-16 | Add Table 7-6-2. |
| | 7-17 | Change the table number and title. |

## Revision History (Contd.)

| Revision | Page | Description |
|---|---|---|
| 1 | 7-18 | Add Table 7-7-2. |
| | 8-1 | Add “based on NB-3600” to the title of Section 8.2. |
| | 8-1 & 8-2 | Add Section 8.3 and change the sentences in Section 8.4. |
| | 8-3 | Change the figure title. |
| | 8-4 | Add Figure 8-2. |
| | 9-1 | Change the 1st sentence of Section 9.0. |
| | 9-1 | Correct the typing error and add the contents to Table 9-1 |
| | 10-1 | Add the words “including 6 nozzles” to the 1st sentence |
| | 10-1 to 10-3 | Change the section numbers and the table numbers. |
| | 10-4 to 10-19 | Add the contents. |
| | 12-1 | Update the revision number of References 4 and 10. |
| | 12-1 | Add References 13 through 16. |
| 2 | Abstract | Change sentences. |
| | i & ii | Revise table of contents. |
| | iii | Revise list of tables. |
| | iv | Revise list of figures. |
| | v | Revise list of acronyms. |
| | 1-1 | Modify sentences and Figure 1-1. |
| | 2-1 | Change contents of Table 2-1. |
| | 3-1 | Modify sentences. |
| | 6-1 | Modify sentences and remove Table 6-2. |
| | 7-1 | Change wording in Table 7-1. |
| | 7-2 | Change contents of Table 7-2 and Table 7-3. |
| | 7-3 | Modify sentences and remove Figure 7-1-2 and Tables 7-5-4 through 7-5-9. |
| | 7-5 to 7-9 | Change contents of Tables 7-5-1 through 7-5-3. |

# Revision History (Contd.)

| Revision | Page | Description |
|---|---|---|
| 2 | 7-10 | Modify sentences and remove Table 7-6-2. |
| | 7-12 | Modify sentences and remove Table 7-7-2. |
| | 8-1 | Remove Section 8.3 and Figure 8-2. |
| | 9-1 | Update contents of Table 9-1. |
| | 10-1 | Change sentence. |
| | 10-3 | Revise stress analysis result. |
| | 10-4 to 10-19 | Remove contents. |
| | 11-1 & 11-2 | Change Figure 11-1 through Figure 11-3. |
| | 12-1 | Update and delete reference documents. |

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# Abstract

This report contains a summary of the structural evaluation of the Reactor Coolant Loop (RCL) piping.

The calculations were based on the loading conditions defined in the US-APWR RCL piping Design Specification (Reference 4) and on the procedures per ASME Boiler & Pressure Vessel Code Section III (Reference 1).

The RCL piping satisfies the applicable structural limits of the 1992 Edition of Section III including the 1992 addenda.

# Table of Contents

# List of Tables

# List of Figures

# List of Acronyms

The following list defines the acronyms used in this document.

| | |
|---|---|
| BAC | Bounding Analysis Curve |
| FE | Finite Element |
| LBB | Leak Before Break |
| RCL | Reactor Coolant Loop |
| RCP | Reactor Coolant Pump |
| RCS | Reactor Coolant System |
| RV | Reactor Vessel |
| SG | Steam Generator |
| SRSS | Square Root Sum of Square |
| SSE | Safe Shutdown Earthquake |
| 1/3 SSE | Level B Service Loading Earthquake |

## 1.0 INTRODUCTION

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

The RCL piping consists of hot leg, crossover leg and cold leg as shown in Figure 1-1.

This report provides structural evaluations for the three parts of RCL piping.

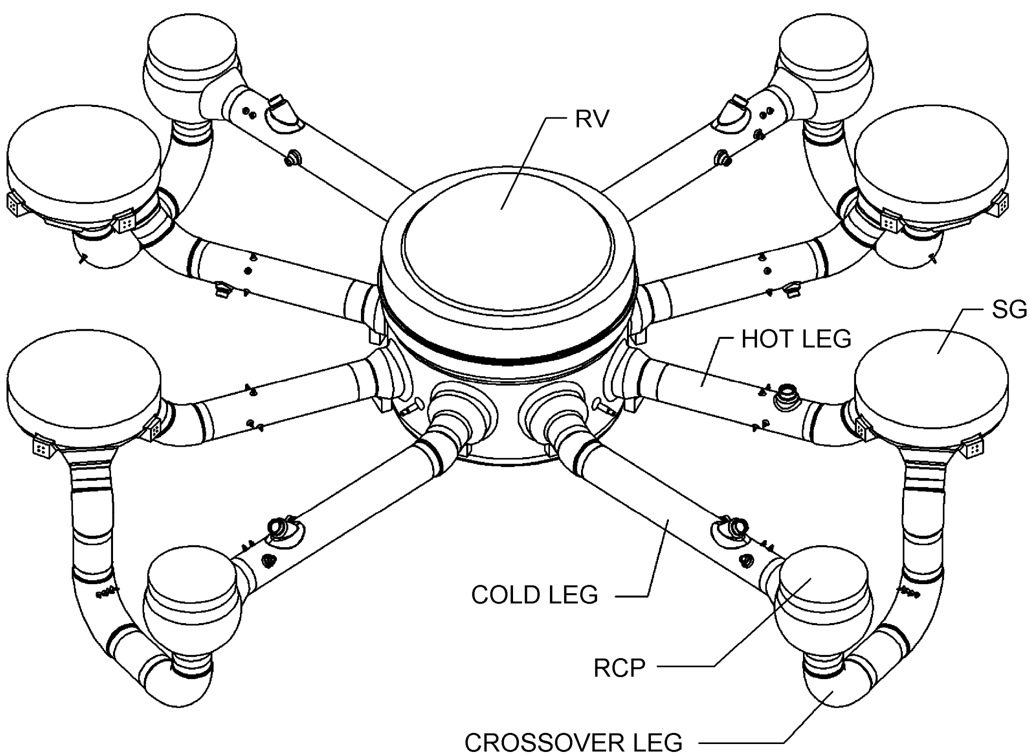



**Figure 1-1 Schematic view of the RCL piping**

## 2.0 SUMMARY OF RESULTS

The most limiting results of the RCL piping are listed in Table 2-1. The structural analysis results and the LBB evaluation results are summarized in Sections 10 and 11 respectively.

**Table 2-1 Summary of Most Limiting Results**

| Section | Evaluated Part | Max Stress / Allowable Ratio (1) | Highest Fatigue Usage Factor (2) | LBB Evaluation |
|---|---|---|---|---|
| 10.1 & 11 | Hot Leg | | | |
| 10.1 & 11 | Crossover Leg | | | |
| 10.1 & 11 | Cold Leg | | | |

Note 1: The max stress / allowable ratio is the ratio of the calculated stress intensity (or pressure) to the allowable stress intensity (or allowable pressure). Therefore, any ratio less than or equal to 1.0 is acceptable.

$$\text{Ratio} = \frac{\text{Calculated stress intensity (or Pressure)}}{\text{Allowable stress intensity (or Allowable pressure)}}$$

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

## 3.0 CONCLUSIONS

The US-APWR RCL piping is designed to the requirements of the ASME Boiler and Pressure Vessel Code, 1992 Edition including the 1992 Addenda for the Design, Service Loadings and Operating Conditions as specified in the Design Specification (Reference 4).

From the results summarized in this report and a review of the piping design drawings, it is concluded that the RCL piping satisfies the requirements of the ASME Code.

## 4.0 NOMENCLATURE

**Table 4-1 Symbols and definition**

| Symbol | Unit | Definition |
|---|---|---|
| $S_m$ | ksi/psi | Design stress intensity |
| $S_y$ | ksi/psi | Yield stress |
| $S_u$ | ksi/psi | Tensile strength |
| $P$ | psi | Design pressure |
| $P_a$ | psi | Maximum allowable internal pressure defined in NB-3641.1 |
| $P_L$ | ksi | General primary membrane stress |
| $P_b$ | ksi | Primary bending stress |
| $Q$ | ksi | Secondary stress |
| $C_4$ | – | Constant number defined in NB-3653.7. (=1.3 for austenitic material) |
| $E$ | psi | Modulus of elasticity |
| $y'$ | – | Constant number defined in NB-3653.7 |
| $\alpha$ | 1/°F | Coefficient of thermal expansion |
| $\Delta T_1$ | °F | Range of temperature difference between $T_o$ and $T_i$ of the piping assuming equivalent linear temperature distribution |
| $T_o$ | °F | Temperature of the outside surface |
| $T_i$ | °F | Temperature of the inside surface |

# 5.0 ASSUMPTIONS AND OPEN ITEMS

## 5.1 Assumptions

All dimensions used in the evaluation (diameter, thickness and bend radius of elbow) are nominal values.

## 5.2 Open Items

There are no open items in this Technical Report.

## 6.0 ACCEPTANCE CRITERIA

The RCL piping is evaluated in accordance with NB-3600.

Table 6-1 specifies the RCL piping stress limits according to NB-3600.

**Table 6-1 RCL Piping Stress Limits according to NB-3600**

| Condition | Stress Category | Stress Limits | Remarks |
|---|---|---|---|
| Design | Primary Stress | 1.5 $S_m$ | NB-3652 |
| Level A/B | Primary Plus Secondary Stress | 3 $S_m$ | NB-3653 |
| | Usage Factor | 1.0 | NB-3653.5 |
| | Thermal Bending Stress | 3 $S_m$ | NB-3653.6 |
| | Primary Plus Secondary Membrane Stress Excluding Thermal Bending and Expansion Stress | 3 $S_m$ | NB-3653.6 |
| | Thermal Stress Ratchet | $\Delta T_1$ range $\leq y' S_y C_4 / (0.7E\alpha)$ | NB-3653.7 |
| Level B | Permissible Pressure | 1.1 $P_a$ | NB-3654.1 |
| | Primary Stress | Min (1.8 $S_m$, 1.5 $S_y$) | NB-3654.2 |
| Level C | Permissible Pressure | 1.5 $P_a$ | NB-3655.1 |
| | Primary Stress | Min (2.25 $S_m$, 1.8 $S_y$) | NB-3655.2 |
| Level D | Permissible Pressure | 2 $P_a$ | NB-3656 |
| | Primary Stress | Min (3 $S_m$, 2 $S_y$) | NB-3656 |

# 7.0 DESIGN INPUT

## 7.1 Geometry

The RCL piping basic drawings used to supply dimensions for the stress evaluation are listed in Table 7-1.

**Table 7-1 RCL Piping Basic Design Drawing List**

| No. | Drawing Title | Reference Number |
|---|---|---|
| 1 | Reactor Coolant Loop Piping Design Drawings | N0-F700L11 |

## 7.2 Material

The materials for the RCL piping are listed in Table 7-2.

**Table 7-2 Materials of Construction**

| Part | Material |
|---|---|
| Straight pipe | SA-336 Grade F316 |
| Elbows | SA-336 Grade F316 |

The material strength properties used in the stress are obtained from ASME Section II.

**Table 7-3 Material Properties for SA-336 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 Design Specification (Reference 4). The following is a summary of those used for the RCL piping structural evaluations.

### 7.3.1 Pressure Loads and Temperature

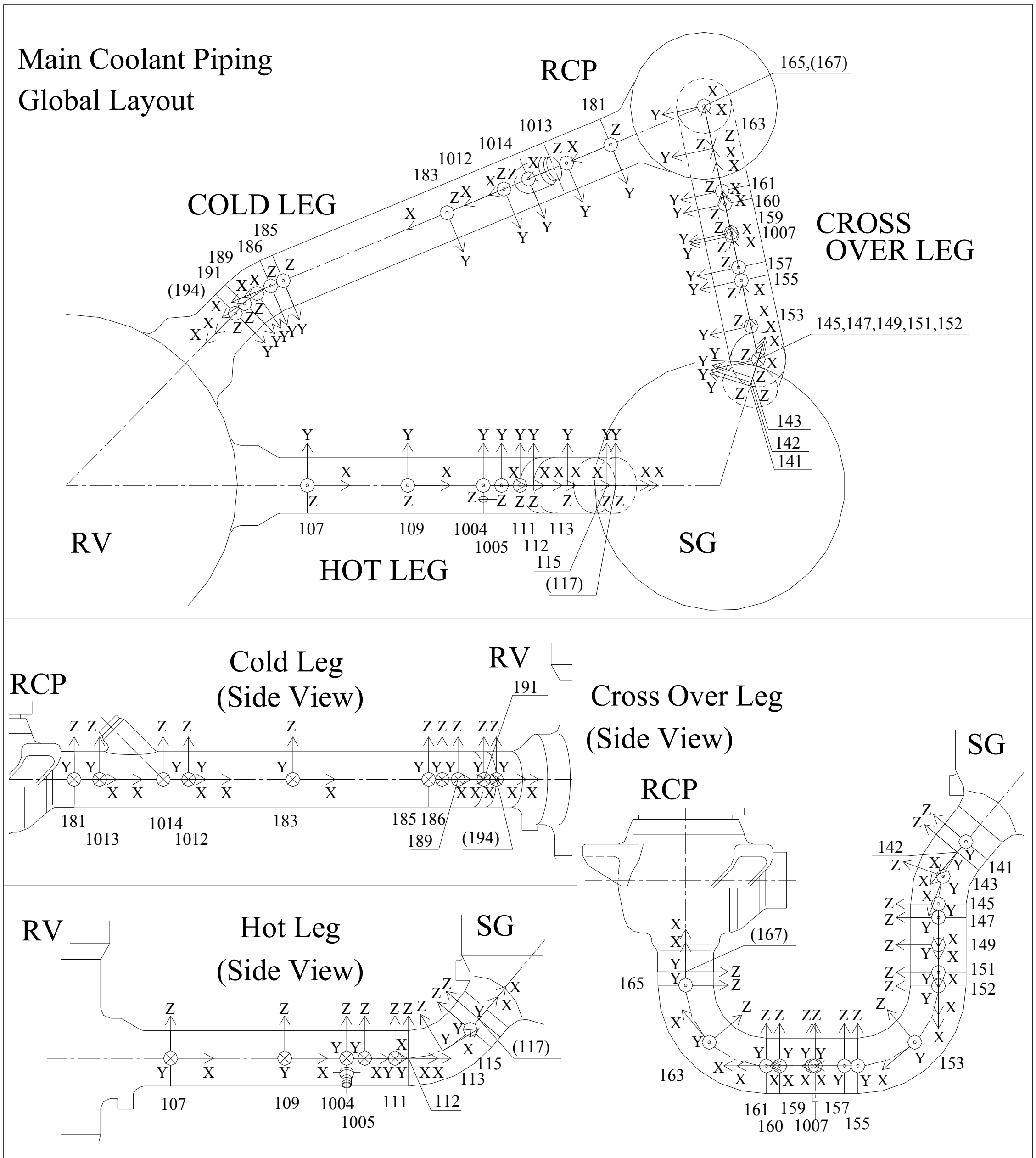
**Table 7-4 Pressures and Temperatures**

| Parameter | Value |
|---|---|
| Design pressure | 2500 psia (2485 psig) |
| Design temperature | 650 $^{o}$F |
| Normal operating pressure | 2250 psia (2235psig) |
| Normal operating temperature (Hot side) | 617.0 $^{o}$F |
| Normal operating temperature (Cold side) | 550.6 $^{o}$F |

### 7.3.2 Mechanical Loads

Mechanical loads are dead weight, thermal expansion load, seismic load and accident load. These loads are obtained from the Design Specification (Reference 4).

Tables 7-5-1 through 7-5-3 provide the member loads of the RCL piping used in the structural evaluations and Figure 7-1-1 shows the coordinate system of the RCL piping.




[NOTE] (1)+X-local axis is set in the coolant flow direction.
(2)Right-handed coordinate system is addopted.
(3)As a rule, piping load shows the load generated at the starting point of the downstream member among evaluation points.
On the other hand the point number added by ( ) shows the load generated at the end point of the upstream member.

**Figure 7-1-1 Coordinate System for RCL piping**

**Table 7-5-1 Member Load of Hot Leg**

| Node No. | Loading | Fx (kips) | Fy (kips) | Fz (kips) | Mx (kips・in) | My (kips・in) | Mz (kips・in) |
|---|---|---|---|---|---|---|---|
| 107 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 109 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 111 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 112 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 113 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 115 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 117 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |

**Table 7-5-2 Member Load of Crossover Leg (1/3)**

| Node No. | Loading | Fx (kips) | Fy (kips) | Fz (kips) | Mx (kips・in) | My (kips・in) | Mz (kips・in) |
|---|---|---|---|---|---|---|---|
| 141 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 142 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 143 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 145 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 147 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 149 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 151 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |

### Table 7-5-2 Member Load of Crossover Leg (2/3)

| Node No. | Loading | Fx (kips) | Fy (kips) | Fz (kips) | Mx (kips・in) | My (kips・in) | Mz (kips・in) |
|---|---|---|---|---|---|---|---|
| 152 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 153 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 155 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 157 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 159 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 160 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 161 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |

**Table 7-5-2 Member Forces of Crossover Leg (3/3)**

| Node No. | Loading | Fx (kips) | Fy (kips) | Fz (kips) | Mx (kips・in) | My (kips・in) | Mz (kips・in) |
|---|---|---|---|---|---|---|---|
| 163 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 165 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 167 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |

### Table 7-5-3 Member Load of Cold Leg

| Node No. | Loading | Fx (kips) | Fy (kips) | Fz (kips) | Mx (kips・in) | My (kips・in) | Mz (kips・in) |
|---|---|---|---|---|---|---|---|
| 181 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 183 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 185 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 186 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 189 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 191 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |
| 194 | Dead Weight | | | | | | |
| | Thermal | | | | | | |
| | Seismic (1/3 SSE) | | | | | | |
| | Seismic (SSE) | | | | | | |
| | Accident | | | | | | |

### 7.3.3 Thermal and Pressure Transient Loads

The design transients used in the structural evaluations are listed in Table 7-6-1.

These transients were determined based on a 60-year plant operating period and are classified into the ASME Level A, Level B, Level C, Level D service conditions, or Test condition, depending on the expected frequency of occurrence and severity of the event.

**Table 7-6-1 Design Transients (1/2)**

| Mark | Transient | Occurrence | Remark |
|---|---|---|---|
| **Level A Service Condition** | | | |
| 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% 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(i) | Steady-state fluctuations and load regulation (Steady state fluctuations) | $1 \times 10^6$ | $P_P \pm 50$psi, $T_{hot}$,$T_{cold}$, $T_{ave} \pm 3.1$F |
| I-h(ii) | Steady-state fluctuations and load regulation (Load regulation) | $8 \times 10^5$ | |
| 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 | |

## Table 7-6-1 Design Transients (2/2)

| Mark | Transient | Occurrence | Remark |
|---|---|---|---|
| **Level B Service Condition** | | | |
| 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 load combinations specified in Reference 4 were used in the structural evaluations. The combinations of pressure, temperatures and member loads are provided in Table 7-7-1.

The names used for member loads refer directly to the names specified in Tables 7-5-1 through 7-5-3.

**Table 7-7-1 Load Combinations for the design based on NB-3600**

| System Operating Condition | Service Stress Limit | Service Loading Combination |
|---|---|---|
| Design | Design | Design pressure (1)(2)<br>Dead weight loads (2) |
| Normal | Level A | Level A thermal & pressure transients<br>Thermal loads |
| Upset | Level B | Level B maximum pressure (1)(2)<br>Level B thermal & pressure transients<br>Dead weight loads (2)<br>Thermal loads<br>Seismic (1/3 SSE) loads |
| Emergency | Level C | Level C maximum pressure (1)(2)<br>Dead weight loads (2) |
| Faulted | Level D | Level D maximum pressure (1)(2)<br>Dead weight loads (2)<br>±SRSS(Seismic(SSE) loads + Accident loads) (2) |

Note 1: Applied to permissible pressure evaluations.
Note 2: Applied to primary stress evaluations.

# 8.0 METHODOLOGY

## 8.1 Heat Transfer Coefficients and Thermal Analysis

The ABAQUS computer program was used to determine temperature distributions of the RCL piping. 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.

Heat transfer coefficients on the inner and outer surfaces of the piping 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 of the piping. The primary coolant temperature versus time curves were applied to all wetted surfaces with appropriate heat transfer coefficients as discussed above. The outside surfaces under the piping insulation were considered adiabatic.

## 8.2 Stress Calculation based on NB-3600

Stress calculation was performed in accordance with NB-3650 using the MCPEVALSI. This program uses input of dimensions, pressure, temperature and load data of the piping, and calculates primary, secondary and peak stress according to the equations described in Appendix 1.

Figure 8-1 shows the stress calculation process.

## 8.3 (Deleted)

## 8.4 Fatigue Analysis Method

The fatigue analysis was based on the rules of NB-3650. This rule requires calculation of the total stress, including the peak stress, to determine the allowable number of stress cycles for the specified Service Loadings. In the RCL piping analysis, the MCPEVALSI was used to calculate fatigue usage factors.

The design transients for Level A and B service conditions (Table 7-6-1) 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 factor equivalent to that for a single SSE event of 20 cycles.

**Figure 8-1 Stress Evaluation Process (NB-3600)**

## 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.<br>ABAQUS is used for thermal analysis in RCL piping evaluation. |
| 2 | MCPFEM | 2.0 | MCPFEM is an MHI Code that makes ABAQUS input files for thermal analysis. |
| 3 | MCPEVALPRI | 2.0 | MCPEVALPRI is an MHI Code that extracts temperature data from ABAQUS output files. |
| 4 | MCPEVALSI | 5.0 | MCPEVALSI is an MHI Code that calculates the stresses and usage factors in accordance with NB-3600. |

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

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

# 10.0 STRUCTURAL ANALYSIS RESULTS

This section summarizes the results of the analyses for the RCL piping.

The stress calculation was performed using computer programs and hand calculations.

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 RCL piping

### 10.1.1 Evaluated Part Dimensions

The RCL piping dimensions are listed in Table 10-1-1.

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**Table 10-1-1 RCL piping dimensions**

| Evaluated Part | Node No. | Outer Diameter (in) | Thickness (in) | Bend Radius of Elbow (in) |
|---|---|---|---|---|
| Hot Leg | 107 | | | |
| | 109 | | | |
| | 111 | | | |
| | 112 | | | |
| | 113 | | | |
| | 115 | | | |
| | 117 | | | |
| Crossover Leg | 141 | | | |
| | 142 | | | |
| | 143 | | | |
| | 145 | | | |
| | 147 | | | |
| | 149 | | | |
| | 151 | | | |
| | 152 | | | |
| | 153 | | | |
| | 155 | | | |
| | 157 | | | |
| | 159 | | | |
| | 160 | | | |
| | 161 | | | |
| | 163 | | | |
| | 165 | | | |
| | 167 | | | |
| Cold Leg | 181 | | | |
| | 183 | | | |
| | 185 | | | |
| | 186 | | | |
| | 189 | | | |
| | 191 | | | |
| | 194 | | | |

### 10.1.2 Stress Results

The stress-to-allowable ratios (calculated stress divided by allowable value), the fatigue cumulative usage factors for the most limiting locations are summarized in Table 10-1-2.

**Table 10-1-2 RCL Piping Stress Result Summary**

| Condition | Stress Category | ASME Ref. | Stress-to-Allowable Ratio | | |
|---|---|---|---|---|---|
| | | | Hot Leg | Cross-over Leg | Cold Leg |
| Design | Primary Stress | NB-3652 | | | |
| Level A/B | Primary Plus Secondary Stress | NB-3653.1 | | | |
| | Usage Factor | NB-3653.5 | | | |
| | Thermal Bending Stress | NB-3653.6 | | | |
| | Primary Plus Secondary Membrane Stress Excluding Thermal Bending and Expansion Stress | NB-3653.6 | | | |
| | Thermal Stress Ratchet | NB-3653.7 | | | |
| Level B | Permissible Pressure | NB-3654.1 | | | |
| | Primary Stress | NB-3654.2 | | | |
| Level C | Permissible Pressure | NB3655.1 | | | |
| | Primary Stress | NB-3655.2 | | | |
| Level D | Permissible Pressure | NB-3656 | | | |
| | Primary Stress | NB-3656 | | | |

## 11.0 LEAK-BEFORE-BREAK EVALUATION

This section describes the leak-before-break (LBB) evaluation results for the RCL piping.

## 11.1 Evaluation Method

The bounding analysis curve (BAC) approach, which is summarized in Appendix 2 of MUAP-09011 (Reference 12), was applied to the evaluation.

## 11.2 Evaluation Results

The BACs for the RCL piping were taken from Reference 11.

The RCL piping stress calculation results were plotted in Figures 11-1 through 11-3.

LATER

**Figure 11-1 Hot Leg LBB Evaluation Result**

LATER

Figure 11-2 Crossover Leg LBB Evaluation Result

LATER

Figure 11-3 Cold Leg LBB Evaluation Result

## 12.0 REFERENCES

1. ASME Boiler and Pressure Vessel Code, Section III, Nuclear Power Plant Components, 1992 Edition including 1992 Addenda
2. ASME Boiler and Pressure Vessel Code, Section II Material Specification, 2001 Edition through 2003 Addenda
3. N0-FB10L01 Rev.3, “US-APWR Standard Design General Design Specification for Class 1 Components”
4. N0-F700L01, Rev.4, “US-APWR Reactor Coolant Loop Piping 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. Eckert and Drake, “Heat & Mass Transfer”, Second Edition, 1959.
8. Frank Kreith, Principles of HEAT TRANSFER third edition, 1976.
9. (Deleted)
10. N0-F700L11 Rev.4, “US-APWR Reactor Coolant Loop Piping Design Drawings”
11. N0-CG00005 Rev.2, “US-APWR Bounding Analysis Curves for Leak Before Break Evaluation”
12. MUAP-09011-P Rev.2, “Summary of Stress Analysis Results for the US-APWR Reactor Coolant Loop Branch Piping”
13. (Deleted)
14. (Deleted)
15. (Deleted)
16. (Deleted)

# Appendix 1

# Reactor Coolant Loop Piping

# Stress Calculation Formula

## 1. Introduction

This Appendix describes the stress calculation formula used in the RCL piping evaluation.

## 2. Design condition

2.1 Primary stress [NB-3652, Eq.(9)]

$$B_1 \frac{PD_o}{2t} + B_2 \frac{D_o}{2I} M_i \leq 1.5 S_m$$

| | |
|---|---|
| $B_1$, $B_2$ | : Stress indices |
| $P$ | : Design pressure, psi |
| $D_o$ | : Outside diameter, in |
| $t$ | : Wall thickness, in |
| $I$ | : Moment of inertia, $in^3$ |
| $M_i$ | : Resultant moment due to dead weight (The other mechanical load is equal to zero for the RCL piping.), in-lb |
| $S_m$ | : Allowable design stress intensity value at the design temperature, psi |

## 3. Level A/B service condition

3.1 Primary plus secondary stress [NB-3653.1, Eq.(10)]

$$S_n = C_1 \frac{P_o D_o}{2t} + C_2 \frac{D_o}{2I} M_i + C_3 E_{ab} \left| \alpha_a T_a - \alpha_b T_b \right| \leq 3 S_m$$

| | |
|---|---|
| $C_1$, $C_2$, $C_3$ | : Stress indices |
| $P_o$ | : Range of pressure, psi |
| $M_i$ | : Resultant range of moment due to the followings, in-lb<br>- Thermal expansion load<br>- Mechanical load (equal to zero for the RCL piping)<br>- Seismic load (only included in 1/3 SSE seismic event) |
| $E_{ab}$ | : Average modulus of elasticity of the two sides at room temperature, psi |
| $\alpha_a$, $\alpha_b$ | : Coefficient of thermal expansion at room temperature, 1/°F |
| $T_a$, $T_b$ | : Range of average temperature of structural discontinuity, °F |
| $S_m$ | : Allowable design stress intensity value at the temperature of normal operation, psi |

The other symbols are same as Section 2.1.

3.2 Peak stress [NB-3653.2, Eq.(11)]

$$S_p = K_1 C_1 \frac{P_o D_o}{2t} + K_2 C_2 \frac{D_o}{2I} M_i + \frac{1}{2(1-\nu)} K_3 E\alpha \left|\Delta T_1\right|$$
$$+ K_3 C_3 E_{ab} \left|\alpha_a T_a - \alpha_b T_b\right| + \frac{1}{1-\nu} E\alpha \left|\Delta T_2\right|$$

| | |
|---|---|
| $K_1$, $K_2$, $K_3$ | : Stress indices |
| $E$ | : Modulus of elasticity at room temperature, psi |
| $\alpha$ | : Coefficient of thermal expansion at room temperature, 1/°F |
| $\Delta T_1$ | : Range of the temperature difference between the temperature of the outside $T_o$ and the temperature of the inside surface $T_i$ of the piping product assuming moment generating equivalent linear temperature distribution, °F |
| $\Delta T_2$ | : Range of the nonlinear thermal gradient through the wall thickness not included in $\Delta T_1$, °F |
| $\nu$ | : Poisson's ratio (=0.3) |

The other symbols are same as Section 3.1.

3.3 Alternating stress and cumulative usage factor [NB-3653.3 to NB-3653.5]

$$S_{alt} = \frac{S_p}{2} \quad \text{for} \quad S_n \le 3S_m$$

Cumulative usage factor (*UF*) is evaluated in accordance with NB-3222.4(e)(5).

$$UF \le 1.0$$

3.4 Simplified elastic-plastic discontinuity analysis

In case of $S_n$ > $3S_m$, the simplified elastic-plastic discontinuity analysis is used.

(a) Thermal bending stress [NB-3653.6(a)]

$$S_e = C_2 \frac{D_o}{2I} M_i^* \le 3S_m$$

| | |
|---|---|
| $M_i^*$ | : Range of moment due to thermal expansion load, in-lb |

The other symbols are same as Section 3.1

(b) Primary plus secondary stress excluding thermal bending and thermal expansion stresses [NB-3653.6(b)]

$$C_1 \frac{P_o D_o}{2t} + C_2 \frac{D_o}{2I} M_i + C_3' E_{ab} \left| \alpha_a T_a - \alpha_b T_b \right| \leq 3S_m$$

$C_3'$ : Stress index

The other symbols are same as Section 3.1

(c) Alternating stress and cumulative usage factor [NB-3653.6(c)]

$$S_{alt} = K_e \frac{S_p}{2}$$

$K_e = 1.0$ , for $S_n \leq 3\mathrm{S_m}$

$K_e = 1.0 + \frac{1-n}{n(m-1)} \left( \frac{S_n}{3S_m} - 1 \right)$, for $3S_m < S_n < 3mS_m$

$K_e = \frac{1}{n}$, for $S_n \geq 3mS_m$

$m$ = 1.7, $n$ = 0.3 for austenitic stainless steel

Cumulative usage factor (*UF*) is evaluated in accordance with NB-3222.4(e)(5).

$UF \leq 1.0$

(d) Thermal stress ratchet [NB-3653.7]

$$\Delta T_1 \text{ range} \leq \frac{y' S_y}{0.7 E \alpha} C_4$$

$y'$ : Refer to the table below.

| $x$ | 0.3 | 0.5 | 0.7 | 0.8 |
|---|---|---|---|---|
| $y'$ | 3.33 | 2.00 | 1.20 | 0.80 |

$x$ : Equal to $(PD_o/2t)(1/S_y)$

$P$ : Maximum pressure for the set of conditions under consideration, psi

$C_4$ : Equal to 1.3 for austenitic stainless steel

$S_y$ : Yield point at the average fluid temperature of the load set, psi

## 4. Level B service condition

4.1 Permissible pressure [NB-3654.1]

$$P_M \le 1.1 P_a$$

$$P_a = \frac{2 S_m t}{D_o - 2yt}$$

| | |
|---|---|
| $P_M$ | : Maximum pressure in Level B service condition, psi |
| $P_a$ | : Maximum allowable internal pressure defined in NB-3641.1, psi |
| $y$ | : Equal to 0.4 |

The other symbols are same as Section 2.1.

4.2 Primary stress [NB-3654.2]

$$B_1 \frac{P_M D_o}{2t} + B_2 \frac{D_o}{2I} M_i \le \mathrm{Min}(1.8 S_m, 1.5 S_y)$$

| | |
|---|---|
| $P_M$ | : Maximum pressure in Level B service condition, psi |
| $M_i$ | : Resultant moment due to dead weight (Mechanical load is equal to zero for the RCL piping.), in-lb |
| $S_m$ | : Allowable design stress intensity value at the maximum temperature in Level B service condition, psi |
| $S_y$ | : Yield strength at the maximum temperature in Level B service condition, psi |

The other symbols are same as Section 2.1.

## 5. Level C service condition

5.1 Permissible pressure [NB-3655.1]

$P_M \leq 1.5 P_a$

$P_M$ : Maximum pressure in Level C service condition, psi

The other symbols are same as Section 4.1.

5.2 Primary stress [NB-3655.2]

$$B_1 \frac{P_M D_o}{2t} + B_2 \frac{D_o}{2I} M_i \leq \mathrm{Min}(2.25 S_m, 1.8 S_y)$$

$P_M$ : Maximum pressure in Level C service condition, psi

$M_i$ : Resultant moment due to dead weight (Mechanical load is equal to zero for the RCL piping.), in-lb

$S_m$ : Allowable design stress intensity value at the maximum temperature in Level C service condition, psi

$S_y$ : Yield strength at the maximum temperature in Level C service condition, psi

The other symbols are same as Section 4.1.

## 6. Level D service condition

6.1 Permissible pressure [NB-3656 (b)]

$P_M \leq 2P_a$

$P_M$ : Maximum pressure in Level D service condition, psi

The other symbols are same as Section 4.1.

6.2 Primary stress [NB-3655.2]

$$B_1 \frac{P_M D_o}{2t} + B_2 \frac{D_o}{2I} M_i \leq \mathrm{Min}(3S_m, 2S_y)$$

$P_M$ : Maximum pressure in Level D service condition, psi

$M_i$ : Resultant moment due to the followings, in-lb
- Dead weight
- Mechanical load (equal to zero for the RCL piping.)
- Seismic load (SSE)
- Accident load

$S_m$ : Allowable design stress intensity value at the maximum temperature in Level D service condition, psi

$S_y$ : Yield strength at the maximum temperature in Level D service condition, psi