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GE Hitachi Nuclear Energy

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ESBWR PCCS CONDENSER STRUCTURAL EVALUATION

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ILLUSTRATIONS

1.0 SCOPE

The design of the Passive Containment Cooling System (PCCS) as described in Revision 6 of the ESBWR Design Control Document (DCD) is being modified to improve its ability to withstand the loads resulting from the buildup and possible detonation of radiolytically generated combustible gases. This report describes these changes and the conservative methodology by which the detonation loads are calculated as well as the design philosophy used to ensure the PCCS has been designed robustly to withstand the most bounding loads while not affecting its heat transfer capability.

This report focuses on the design of the PCCS condenser tubes, as they are thin-walled and more susceptible to internal overpressure. This report also addresses how this same methodology is applied in a more comprehensive structural analysis of the condenser and its supports.

2.0 METHODOLOGY

The PCCS components are first evaluated for accumulation of radiolytic hydrogen and then the possible range of mixture concentrations is determined. A bounding detonation pressure for a pure stoichiometric mixture of hydrogen and oxygen is calculated using the highest peak pressures during a loss of coolant accident (LOCA). It is then applied statically using dynamic load factors (DLF) in a finite element model for the PCCS condenser using the approved ANSYS computer code. The calculated stresses for the detonation load are combined with those from seismic and LOCA thermal loads. The acceptance criterion for the PCCS condenser is based on Service Level D limits in ASME Code Section III, Subsection NE for elastic-plastic analysis. Two postulated detonation scenarios are analyzed in the finite element model, a detonation in one tube and a detonation in the lower drum.

Sizing calculations are performed for the PCCS tubes to provide an initial wall thickness such that the primary membrane stress meets Service Level D ASME Code Section III, Subsection NE acceptance criteria for elastic-plastic analysis. Impact of increased tube thickness on heat removal capacity is estimated and compensated by adding additional tubes. This configuration is evaluated in Appendix B.

2.1 COMBUSTIBLE GAS GENERATION / CONCENTRATION

The radiolytic generation of combustible gas is a common occurrence in typical power reactors, including ESBWR. The generation of hydrogen and oxygen gas occurs in a stoichiometric ratio at a rate proportional to the core decay heat. During a LOCA, these gases escape into the containment resulting in very dilute concentrations of combustible gas in the drywell (below concentrations that could result in ignition). The PCCS contains six condensers that are designed to receive this mixture of steam and noncondensable gas, condense the steam, and return the condensate back to the drywell. See simplified sketch, Figure 1, of the PCCS Condenser.

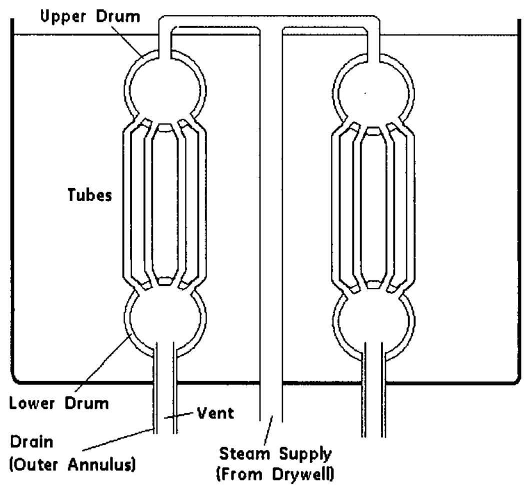

Figure 1: PCCS Condenser Simplified Sketch

Each PCCS condenser consists of two modules submerged in a pool of cooling water. Each module contains an upper and lower drum connected by an array of 2-inch diameter tubes. Gas from the drywell passes up a central supply line that feeds both upper drums. The steam component of the gas condenses as it moves downward through the tube array (transferring its heat to the pool water) and condensate collects in the lower drum and drains back to the drywell by gravity. The pool water level drops slowly over the course of the accident as water boils off.

The leftover noncondensable gas can exit the PCCS condenser through a vent line that connects the lower drum to the wetwell. As steam and noncondensables enter, the vent operates passively to bleed gas from the lower drum of the condenser when there is a sufficient pressure differential between the drywell and wetwell. In this way, something close to an equilibrium state is reached in which noncondensables persistently linger in the condenser while small amounts continue to come in with the steam and go out through the vent.

In the initial stage of a LOCA, the majority of the noncondensable gas in the drywell is nitrogen. This gas is eventually forced into the wetwell by the depressurization of the Reactor Pressure Vessel (RPV). Over time, the primary source of noncondensable gas in the drywell is the radiolytically generated hydrogen and oxygen. It has been shown in TRACG that noncondensable gas accumulates in the lower portions of the tubes and lower drum. When this gas transitions from mostly nitrogen to a stiochiometric mixture of hydrogen and oxygen, a combustible concentration may exist.

The relative concentration of steam to hydrogen and oxygen in the PCCS condenser is highly dependent on the conditions in the Isolation Condenser /Passive Containment Cooling System (IC/PCCS) pool subcompartment. Lower pool temperatures will bring down the temperature inside the condenser thereby lowering the steam fraction. The pool level can influence the variation in steam fraction over the height of the condenser tubes. For example, the steam fraction in the tubes could vary from as little as 0.002 to 0.25. The steam fraction of 0.002

assumes a pool temperature of 4 °C; the steam fraction of 0.25 assumes boiling in the pool. See Table 3-1 for an evaluation of steam fractions in other PCCS components.

In order to ensure a conservative methodology, the atmosphere inside the PCCS is assumed to be 67% hydrogen and 33% oxygen (no steam):

	H_2	O_2	Steam
Lower Tubes	50% - 67 %	25% - 33%	0.2% - 25%
Lower Drum	50% - 67 %	25% - 33%	0.2% - 25%

PCCS Bounding Mixture
for Detonation Analysis

H_2	O_2	Steam
67%	33%	0%

Figure 2: Bounding PCCS Gas Fraction

Also, the initial PCCS pressure is assumed equivalent to the peak drywell pressure (407 kPa absolute) for the bounding containment LOCA even though the actual pressure inside the condenser will be significantly lower due to condensation. This approach is conservative because it results in a pure mixture (free from steam diluent) and assumes it is at an initial density greater than it could realistically achieve.

2.2 DETONATION LOADS

The process by which a detonation wave propagates through a medium and imparts stress on its surroundings is a complex subject that has been studied for a variety of applications. References 1 through 9 are reports that attempt to characterize this phenomenon. Data from these reports have been used to determine a bounding detonation load.

The entire PCCS is considered, but the focus of this report is on the condenser tubes because of their relatively thin walls that make them more vulnerable to internal overpressure. The other portions of the PCCS (drums, vent and drain piping) are considered separately in this report.

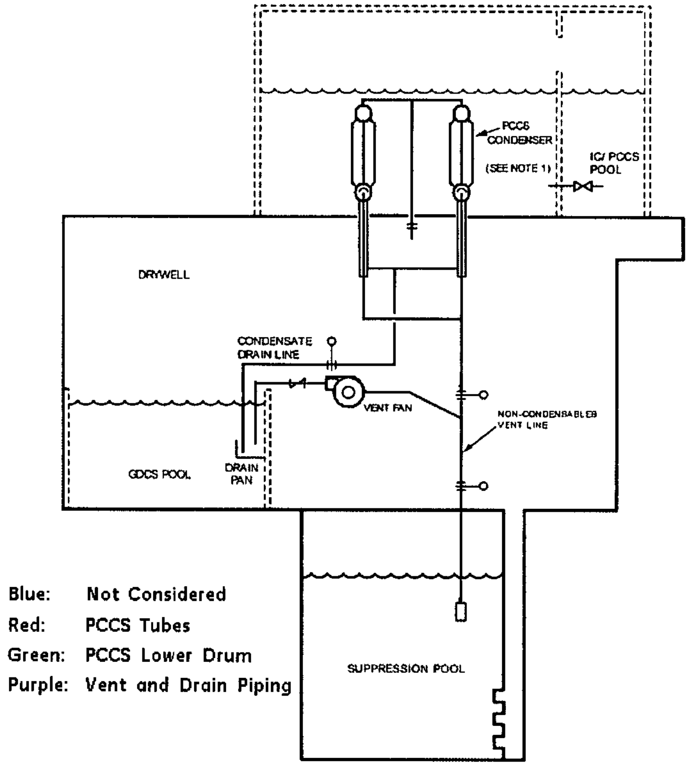

Figure 3: Portions of PCCS Considered for Detonation

The steam supply line and upper drums are not considered in this evaluation because they are constantly being flushed by steam coming from the drywell. The hydrogen and oxygen in this mixture is too dilute to support combustion.

The process used to evaluate the PCCS loads will first estimate the peak pressure resulting from detonation, and then apply this pressure in a finite element model as a static load multiplied by a dynamic load factor.

2.2.1 Peak Pressure Ratio

Many of the studies referenced in Section 6.0 describe the resultant pressure following the passage of a detonation wave, often called the Chapman-Jouguet pressure (or CJ pressure). It has been shown that a correlation can be made between the CJ pressure and the initial pressure prior to detonation. The correlation is dependent on the composition of the fuel-oxidizer mixture, the initial conditions (pressure and temperature), and the geometry of the system.

2.2.1.1 Gas Composition

Reference 3 describes a ratio between CJ pressure and initial pressure for a variety of fuel-oxidizer mixtures. For a stoichiometric mixture of hydrogen and oxygen at an initial temperature of 25°C, this ratio is given as 19:1 (See Table 1 of that report). This ratio is applicable for the PCCS, which also assumes a pure stoichiometric mixture (a conservative assumption given the fact there will be at least a small amount of steam diluent).

2.2.1.2 Initial Conditions

References 2 and 7 show that lower initial temperatures result in higher peak pressure ratios. Realistic temperatures inside the PCCS at the time of detonation would be approximately 100°C. The assumption of 25°C is considerably lower than the expected temperatures inside the PCCS prior to a detonation and therefore more conservative. Likewise, the initial pressure is assumed to be 407 kPa absolute, which is equivalent to the peak drywell pressure during the most limiting LOCA. Even when the drywell is at this peak pressure, the actual pressure in the PCCS will be considerably lower due to its inherent design (submerged in a pool of cooling water). In this way, the initial conditions for the PCCS are conservatively bounded in the context of the 19:1 peak pressure ratio.

2.2.1.3 PCCS Geometry

Much of the literature cited in Section 6.0 discusses testing using simple straight-tube experiments. These simplified geometries are not necessarily representative of the PCCS condenser, which has a more complex shape with upper and lower drums connected by tubes bending at angles ranging from [[ ]]. The presence of bends, constrictions, and closed ends creates opportunities for reflections that can create localized peak pressures in excess of the CJ pressure. Reference 9 characterizes this peak pressure for a closed volume as a maximum of 2.5 times the CJ pressure.

The design of the PCCS condenser (in particular the tubes) is more benign than the tested configuration in Reference 9. Although the condenser tubes do contain bends that are subject to reflection loads, these bends are not as severe as a closed vessel that reflects the full force of the detonation wave. The tube bends range from [[ ]] to a maximum of [[ ]], and all have a bend radius of [[ ]]. Although the presence of bends will introduce some loading due to reflection, the loading will not be to the degree of a closed terminal end. Therefore, the multiplier of 2.5 is a conservative selection for the PCCS to account for effects that could amplify the internal pressure beyond the CJ pressure. The closest geometry in the PCCS to a closed end is the portion of the vent line that terminates in the suppression pool where the water surface would reflect the detonation wave; however, these regions are more easily reinforced to accommodate the additional load.

Using the methodology described above, the peak pressure for the PCCS is determined as:

407 kPa (initial pressure) • 19.0 • 2.5 = 19.3 MPa absolute

2.2.2 Dynamic Load Factor (DLF)

The dynamic load factor (DLF) is a multiplier that is factored into the peak static pressure to determine a maximum bounding load that accounts for dynamic effects resulting from a detonation.

2.2.2.1 DLF Dependence on Detonation Velocity

Reference 3 provides guidance on selecting an appropriate DLF. That study correlates the DLF (also called an amplification factor) to the velocity at which the detonation wave propagates. Low wave speeds are shown to have correspondingly low DLFs (approximately 1). As the wave reaches a "resonance" velocity, the DLF is observed to be as high as 4. At velocities above this resonance threshold, the DLF is shown to decrease and plateau around 2.

The resonance velocity is a characteristic of the tube in which the detonation occurs. A formula for calculating the characteristic resonance velocity or critical velocity (V_{c0}) for the PCCS tubes is given in Reference 3 as:

$$V_{c0} = \left[\frac{E^2 h^2}{3\rho^2 R^2 \left(1 - \nu^2\right)} \right]^{1/4} \tag{1}$$

where

E = Young's modulus

h = tube thickness

ρ = density

R = mean radius

ν = Poisson's ratio

When these parameters are applied in accordance with the revised PCCS condenser tube design (see Section 2.3), the equation becomes:

[[

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2.2.2.2 Determination of a Conservative Detonation Velocity

Reference 1 describes detonation velocities for a pure stoichiometric mixture of hydrogen and oxygen. The velocities reported there (Figure 1 of that report) are in excess of 2800 m/s, which is considerably higher than the V_{c0} value of [[ ]]. However, a pure mixture is not necessarily representative of the mixture in the PCCS (although it has conservatively been assumed so in Section 2.2.1.1), and there is also data to suggest that the presence of steam or other diluents could slow the propagation of the detonation wave. To justify using a DLF of 2, it is important to consider the effects of various diluents to ensure that the most limiting case does not reduce the detonation velocity to a value near V_{c0}.

Reference 10 is a study in which the main focus is on detonation cell widths; however, detonation wave velocity data is also collected and presented with varying dilutions of helium and steam (Figure 2 of that report). The data shows a case with 10% steam and no helium in which there is a small velocity reduction to about 2700 m/s. The data for a dry mixture shows that as helium concentrations approach zero, the velocity approaches a value of approximately 2800 m/s, which is in good agreement with Reference 1. Although this small reduction in velocity is promising, the result of 2700 m/s cannot be considered bounding because steam concentrations in the PCCS can exceed 10%. For the purpose of this evaluation, a steam fraction of 80% is considered bounding because such a mixture lies on the fringe of the lower flammability limits described in Reference 11 (see Figure 1 of that report). However, the studies referenced above do not have data describing detonation velocities at such high steam concentrations.

Because of the lack of experimental data at high steam concentrations, the effects of steam on detonation velocity will be evaluated using a substitute diluent. Reference 6 compares various computational methods for predicting the detonation behavior of various mixtures, including hydrogen and oxygen diluted by argon. Data is presented (Figure 1 of that report) showing that even at concentrations as high as 80% argon, the detonation velocity is still in excess of 1500 m/s. Argon is considered a more effective diluent for reducing detonation velocity due to the dependence of such behavior on the molecular weight of the diluent. Argon is considerably heavier than steam - unlike helium, which is actually shown to increase the speed of the detonation wave. The helium data, which is shown plotted along with argon, is in very close agreement with the experimental helium data described above in Reference 10. This agreement provides confidence in the computational methodology and assurance that even a diluted mixture of hydrogen and oxygen will remain above the PCCS tube V_{c0} value.

2.2.2.3 DLF Summary

The PCCS condenser tubes will be evaluated with a DLF of 2 (other portions of the PCCS will be considered separately).

The DLF is shown to be highly dependent on the speed of the detonation wave. For a given geometry, there is a characteristic resonance velocity at which a DLF of 4 should be used. This characteristic velocity for the PCCS condenser tubes is 1100 m/s. For velocities sufficiently higher than this resonance value, a DLF of 2 is appropriate.

The detonation velocity is highly dependent on the composition of the gas mixture. For the purpose of estimating a peak static load, it is assumed that the PCCS contains a pure stoichiometric mixture of hydrogen and oxygen. For the purpose of estimating detonation velocities, it is more conservative to assume a high amount of dilution that could bring the velocity down into the resonance range. Although these assumptions are in contradiction with one another, they are both conservative in the context in which they are applied.

A literature review identified several studies that evaluate the velocity of a hydrogen-oxygen detonation wave for a pure mixture and in the presence of diluents. The results show that for a conservatively diluted mixture, the velocity is still in excess of 1500 m/s (significantly higher than 1100 m/s). Thus the DLF of 2 is justified.

The bounding detonation load for the condenser tubes is therefore:

407 kPa (initial pressure) • 19.0 • 2.5 • 2 = 38.7 MPa absolute

DLFs for other PCCS condenser components are given in Table 3-3.

2.3 INITIAL SIZING AND STRESS CALCULATION

The design of the PCCS condenser as described in DCD Revision 6 is not considered robust enough to withstand the very conservative detonation loads postulated in the sections above. This section describes the methodology by which the design is modified to withstand a detonation.

A seismic and hydrodynamic analysis was performed for the PCCS condenser (See Appendix A) and is described in the DCD. This analysis will be redone to include detonation loads (as described in Appendix B). The new analysis will reflect the configuration changes described below:

- PCCS condenser tube material changed to SA312 TP XM-19
- PCCS condenser tube thickness changed to [[ ]]
- Number of tubes for each module increased from 280 to [[ ]] (there are two modules in each PCCS condenser)

2.3.1 Design Criteria

The PCCS condenser is designed to ASME Section III, Subsection NE as a Class MC component. As such it must be designed to accommodate the loads within the acceptance criteria stated in that part of the Code.

For the purpose of a preliminary scoping evaluation, detonation loads are evaluated under Service Level D allowable for elastic analysis. These allowables are determined by the following set of criteria from Section NE-3221.1(c) of the Code:

P_m shall not exceed the greater of the following:

A) 85% of the values stated in Appendix F:

Appendix F allowable (Section F-1331.1(a)) is the lesser of $2.4S_m$[1] or $0.7S_u$[1]

[1] Material properties are derived from Part D of the ASME Code at a temperature of 300°F

S_m = 31.4 ksi = 216.5 MPa; 0.85·2.4·216.5 = 442 MPa.

S_u = 94.2 ksi = 649.5 MPa; 0.85·0.7·649.5 = 386 MPa.

B) The Service Level C allowable, which for integral and continuous structures is the greater of 1.2·S_{mc} (S_{mc} is equivalent to 1.1·S_m), or 1.0·S_y.

1.2·1.1·S_m = 286 MPa.

1.0·S_y = 299 MPa.

The appropriate allowable is given by Criterion A: 386 MPa.

2.3.2 Primary Membrane Stress

The primary stresses for the PCCS condenser tubes are given as:

$$\sigma_t = \frac{Max\ Internal\ Load \cdot D}{2t}, \tag{3}$$

where the max internal load is the 38.7 MPa from Section 2.2, and D is the tube ID [[

]]

This result of this preliminary calculation shows predicted stresses [[

]]. The tube sizing described in Section 2.3 will therefore be used as an input for the finite element model described in Appendix B, which will consider plastic-elastic effects. The outcome of that analysis will ultimately determine whether the stresses are within the allowable, and to what degree the tubes need additional reinforcement.

2.4 EFFECT ON HEAT TRANSFER

An increase in tube thickness will increase conduction resistance through the tube wall, which will have a negative effect on the overall heat transfer coefficient of the condenser. To compensate for this effect, the number of tubes is increased in proportion to the degradation in the overall heat transfer coefficient to maintain PCCS heat removal capacity.

The conduction through the tube wall is only one contributor to the overall heat transfer coefficient, which also depends on the convective properties of the inner and outer surface of the tubes. The heat transfer is expressed below with respect to the inner surface of the tube:

[[

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2.5 POSTULATED DETONATION SCENARIOS

The two detonation scenarios analyzed in Appendix B are for a detonation in one PCCS tube and in the PCCS lower drum. Multiple simultaneous detonations are not postulated. Detonations do not propagate into a component where a detonation has already occurred.

2.5.1 Detonation in Tubes

The detonation wave in a tube travels into the upper and the lower drums with it quenching in upper drum due to high steam fractions and with a possibility of reflecting back into the tube once it reaches the lower drum wall. This reflection is accounted for in the peak pressure ratio of 2.5 times 19.0 used in determining the detonation pressure for the PCCS condenser.

2.5.2 Detonation in Lower Drum

A postulated detonation in the lower drum will vent through the tubes. The potential for the reflected waves at the flanges to amplify the detonation pressure are accounted for by the 2.5 factor.

2.6 DISCUSSION OF UNCERTAINTY AND CONSERVATIVE ASSUMPTIONS

The methodology described in this report relies heavily upon theory from literature and experimental data from scientific reports. Because of the complexity and uncertainty associated with predicting detonation properties, this report has made conservative assumptions as appropriate. These assumptions are summarized below.

2.6.1 Overestimation of Radiolytic Gas Concentration

In Section 2.1, it is stated that the initial gas mixture inside the PCCS is a pure stoichiometric mixture of hydrogen and oxygen with no steam presence. This is not a realistic scenario, especially for the upper drum and upper portion of the tubes in which less condensation will have taken place. By assuming a pure stoichiometric mixture, this methodology maximizes the amount of combustible gas in the condenser.

2.6.2 Overestimation of Initial Pressure

As described in Section 2.2, the initial PCCS pressure prior to a detonation is assumed to be the drywell peak pressure following the most limiting LOCA. Because of the inherent design of the PCCS the pressure in the system will always be lower than the drywell pressure, and will not reach a value as high as 407 kPa. For the majority of the accident, the drywell pressure is actually much lower than this, and slowly increases to a peak value over the course of the first 3 days. This trend is illustrated in Table 6.2-14e11 of the ESBWR DCD. The overestimation of initial pressure is a conservative assumption to address uncertainties associated with the experimentally determined peak pressure ratio of 19.0.

2.6.3 Underestimation of Initial Temperature

As described in Section 2.2, the ratio of peak pressure to initial pressure is also dependent on the initial temperature. The references cited in the section have concluded that a lower initial temperature, which allows for a denser mixture of combustible gas, results in a higher peak pressure ratio.

The ratio of 19.0 used in this report was taken from experimental data in which a stoichiometric mixture of hydrogen and oxygen was detonated at an initial temperature of 25°C. The realistic temperature inside the PCCS remains steady in the range between 90°C - 100°C. The underestimation of initial temperature is a conservative assumption to address uncertainties associated with the experimentally determined peak pressure ratio of 19.0.

2.6.4 Bounding the Effects of Tube Bend Reflections

Section 2.2 discusses the bends associated with the PCCS tubes. The literature referenced in Section 6.0 provides experimental data to account for amplification due to the presence of bends or tees. Reference 9 states that the peak pressures resulting from reflected waves in closed vessels are "approximately 2.5 times higher than the CJ pressure". Because the tubes in the PCCS condenser are bent to angles no greater than [[ ]] with bend radii of [[ ]], they are considered less susceptible to reflections than the case in Reference 9, yet the full 2.5 factor is applied for conservatism prior to the application of a dynamic load factor (which is determined in 2.2.2).

2.6.5 Critical Velocity for Bounding DLF Estimate

Following the guidance of Reference 3, the V_{c0} calculated for the PCCS condenser tubes was 1100 m/s, which is considerably less than the detonation velocity 2800 m/s for the assumed stoichiometric mixture of hydrogen and oxygen in the PCCS. However, the conservative determination of peak pressure is not necessarily conservative for the determination of DLF. Therefore, a mixture of 80% diluent and 20% combustible gas was used to determine DLF. The lack of velocity data for mixtures rich in steam required the substitution of argon data. Argon, since it is heavier than steam, is considered a more effective diluent in terms of reducing detonation velocity. The theoretical detonation velocities for a mixture that is 80% argon was shown to still be significantly higher than V_{c0} for the tubes. It is also worth noting that such a lean mixture would likely result in much lower peak pressures.

2.6.6 Elastic Range of Material

The design requirements use acceptance criteria that are within the elastic range of the materials used; therefore the material response will be elastic in the range when subjected to a detonation load.

The reported Reference 15 response of a tube with 15 mm ID and 3 mm wall thickness subjected to hydrogen/oxygen detonations with initial pressures up to 20 bar remained within the elastic range. The tube material had comparable yield and ultimate strength to that of SA-312 TP XM-19. The PCCS condenser is analyzed at much lower initial pressure of about 4 bar.

2.6.7 Lower and Upper Bound Burst Pressure Estimation

Using the method described in Reference 15, the lower bound and upper bound burst pressures for the PCCS tubes are estimated at 41.2 MPa and 56.5 MPa, respectively. The tubes are conservatively designed to a detonation pressure of 38.7 MPa, which is below the lower bound burst pressure.

3.0 CONSIDERATION FOR OTHER PCCS COMPONENTS

Section 2.0 of this report discussed the methodology for calculating detonation loads for the tubes of the PCCS condenser. This section extends that methodology to include the lower drum of the condenser as well as the vent and drain piping.

3.1 PCCS COMPONENT STEAM CONCENTRATIONS

Table 3-1 lists PCCS condenser components and connected piping with steam concentrations. The lower flammability limit of hydrogen, oxygen, and steam mixtures is 80% steam, per Reference 11 (see Figure 1 of that report). A bounding mixture of 100% hydrogen and oxygen is used for mixtures of less than 80% steam.

Table 3-1: PCCS Component Steam Concentration

Component	Steam Concentration[1], x
Steam Supply Piping and Upper Drum)	Note 2
Tubes[3]	$0.002 < x < 0.25$
Lower Drum	$0.002 < x < 0.25$
Vent Pipe (pool)	$0.002 < x < 0.25$
Vent Pipe[4] (drywell)	$0.002 < x < 0.25$
Drain Pipe[4] (pool)	$0.002 < x < 0.25$
Drain Pipe[4] (drywell)	$0.002 < x < 0.25$

1) Partial pressure of steam to total pressure.

2) These components are continuously purged with incoming steam from the drywell, which is composed of mostly steam with diluted amounts of hydrogen and oxygen.

3) Low steam fraction calculated using saturated steam pressure with assumed pool water temperature of 4.4 °C.

4) These components receive the steam mixture from the PCCS tubes. For drywell components, credit is not taken for any water vaporizing due to higher drywell temperatures.

3.2 APPLICABLE SUBSECTIONS OF ASME CODE SECTION III

The applicable subsection of ASME Code Section III for each PCCS component is given in Table 3-2. The acceptance criteria are based on Service Level D for elastic analysis.

Table 3-2: PCCS Components Applicable ASME Code III Subsection

Component	ASME Code Section III, Subsection
Steam Supply Piping (drywell)	NE
Steam Supply Piping (pool)	NE
Upper Drum	NE
Tubes	NE
Lower Drum	NE
Vent Pipe (pool)	NE
Vent Pipe (drywell)	NC
Vent Fan Pipe[1] (drywell)	NC
Drain Pipe (pool)	NC
Drain Pipe (drywell)	NC

1) Vent fans and vent fan piping are nonsafety-related components but are conservatively designed to the criteria in Subsection NC.

3.3 PCCS COMPONENT DETONATION LOADS

The detonation loads for the condenser lower drum are calculated the same way as in Section 2.2 and 2.3. The bounding static pressure of 19.3 MPa is applicable for all portions of the PCCS. The DLF, however, is subject to change based on the characteristic V_{c0} velocity of the component and the presence of severe bends.

Eqn. 1 is used to determine characteristic velocities for the lower drum and vent and drain piping as shown in Table 3-3.

Table 3-3: Evaluation of Other Components of the PCCS

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4.0 CONSIDERATION FOR ICS

The Isolation Condenser System (ICS) contains four condensers that are of a tube-and-drum design similar to the PCCS condensers. During a LOCA, these condensers are also vulnerable to the buildup and detonation of combustible gases.

4.1 ICS COMPONENT STEAM CONCENTRATIONS

Table 4-1 lists ICS condenser components and connected piping with steam concentrations. The lower flammability limit of hydrogen, oxygen, and steam mixtures is 80% steam, Reference 11 (see Figure 1 of that report). A bounding mixture of 100% hydrogen and oxygen is used for mixtures of less than 80% steam.

Table 4-1: ICS Components Steam Concentration

Component	Steam Concentration[1], x
Steam Supply Pipe	Note 2
Upper Drum[3]	0.3 < x < 1.0
Tubes	0.0 < x < 0.30
Lower Drum	0.0 < x < 0.30
Vent Pipe (pool)	0.0 < x < 0.30
Vent Pipe[4] (drywell + wetwell)	N/A
Drain Pipe[5] (pool)	0.0 < x < 0.30
Drain Pipe[5,6] (drywell)	0.0 < x < 0.30

1) Partial pressure of steam to total pressure.

2) Steam supply pipe is continuously purged with incoming steam from the reactor pressure vessel, which is composed of mostly steam with diluted amounts of hydrogen and oxygen.

3) Due to slow condensation rates the steam flow into upper drum is not sufficient to keep it purged. After the water level drops and exposes the upper drum, steam fractions rise to 1.0.

4) Vent lines do not open during LOCA conditions and remain full of water.

5) These components receive steam mixture from the ICS tubes. For drywell components, credit is not taken for any water vaporizing due to higher drywell temperatures.

6) Drain pipe in the drywell remains partially filled with water where the level will depend on the level inside the reactor pressure vessel. For Main Steam Line Break (MSLB) LOCA, the level is at the steam line elevation.

4.2 ICS STRUCTURAL EVALUATION

The ICS condensers are designed to be considerably more robust than the PCCS condensers. The tubes are of the same outer diameter, but with wall thicknesses of [[ ]]. The material of construction is modified Alloy 600, which has an ultimate strength similar to XM-19. Any differences in strength and thickness will be accounted for when the ICS structural evaluation is performed.

There is a requirement in Revision 7 of the DCD to perform an evaluation of the ICS (Tier 1, Table 2.4.1-3, Items 2a1 and 2b1) and PCCS (Tier 1, Table 2.15.4-2, Items 2a1 and 2b1) that includes consideration for combustion loads. This evaluation for PCCS is described in Appendix A (modified by Appendix B to include detonation). A similar evaluation will be performed for the ICS to validate the design using the same methodology described in this report.

4.3 APPLICABLE SUBSECTIONS OF ASME CODE SECTION III

The applicable subsection of ASME Code Section III for each ICS component is given in Table 4-2. The acceptance criteria are based on Service Level D for elastic analysis.

Table 4-2: ICS Components Applicable ASME Code III Subsection

Component	ASME Code Section III, Subsection
Steam Supply Pipe (drywell)	NB
Steam Supply Pipe up to Venturi (pool)	NB
Steam Supply Pipe from Venturi to Upper Drum (pool)	NC
Upper Drum	NC
Tubes	NC
Lower Drum	NC
Vent Pipe (pool)	NC
Vent Pipe (drywell + wetwell)	NC
Drain Pipe from Lower Drum to Tee Connection (pool)	NC
Drain Pipe from Tee Connection in Pool to Reactor Pressure Vessel	NB

5.0 PCCS AND ICS INSPECTIONS

During plant outages, routine in-service inspection is required for the isolation condensers, piping, containment, penetration sleeves, and supports according to ASME B&PV Code Section III and Section XI (requirements for design and accessibility of welds).

5.1 PCCS AND ICS IN-SERVICE INSPECTIONS

Examination of welds shall be in accordance with NE-5000. Visual examination of tube-to-header (drums) welds can be performed for both sides. The ends of the upper and lower drums are removable to provide access to the interior of the unit.

5.2 PCCS AND ICS FABRICATION INSPECTIONS

5.2.1 Tube-to-Header Welds

During fabrication, PCCS and ICS tube-to-header welds shall be examined by PT, meeting the requirements of NE-5350.

5.2.2 Tube Bends

PCCS tubes bent by cold forming shall be annealed after bending. Annealing shall be required for bend radii < 20D. Annealing shall be conducted between 1065°C and 1120°C, followed by a quench to 205°C within 5 minutes. Process includes tube bends + 150 mm on each side. Interior of tubes is purged with a protective atmosphere during the process.

Tube thickness shall be verified post-bending. A qualification sample with smallest bend radius shall be sectioned to confirm wall thickness requirement is met.

The hardness of XM-19 for PCCS tubes is limited to Rockwell C 30 for the final product.

5.2.3 Weld and Weld Filler Material

Tube-to-header weld filler metals used shall be 308L, 309L, and 316L.

6.0 REFERENCES

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4. F. Pintgen, Z. Liang, and J. E. Shepherd, "Structural Response of Tubes to Deflagration-to-Detonation Transition". Extended abstract for 21rst International Colloquium on the Dynamics of Explosions and Reactive Systems, Poitiers, France, 23-27 July 2007.

5. NUREG/CR-4905, "Detonability of H2-Air-Diluent Mixtures". Sandia National Laboratories, June 1987.

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13. NEDC-32615P, "Post-Test Analysis of PANTHERS PCC Tests". GE Nuclear Energy, June 1996.

14. "PANTHERS-PCC Data Analysis Report". SIET Document No. 00394RA95, Rev. 0. June 20, 1995. Transmitted under MFN 098-95, Docket STN 52-004.

15. M. Kuznetsov et al., "Structural Response of DN15-Tubes Under Radiolysis Gas Detonation Loads for BWR Safety Applications". 18th International Conference of Structural Mechanics in Reactor Technology (SmiRT 18), Beijing, China, August 7 – 12, 2005, SmiRT 18-J09-1.

APPENDIX A - ESTABLISHED PCCS STRUCTURAL ANALYSIS

A.1 Description of Model

A finite element analysis model (FEM) using the approved ANSYS computer code was performed on the PCCS condenser with a supplemental hand calculation. Approved versions of ANSYS are given in ESBWR DCD Tier 2, Table 3D.1-1.

- The FEM models the current geometry of the PCCS condenser and supports described in Figures A.1-1a, A.1-1b, and A.1-2, including all components between the steam inlet passages through the RCCV Top Slab and the condensate drain/vent passages through the RCCV Top Slab.
- The following components of the PCCS condenser were modeled with [[ ]] ANSYS elements:
  - [[
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- The tubes of the PCCS condenser were modeled with [[ ]] ANSYS elements with the following properties:
  - [[
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  -]]

- The [[ ]] of the dynamic steel frame were modeled with [[ ]] ANSYS elements with the following properties:
  - [[
  -
  -
  -
  -
  -]]

A.2 Load Definitions

Consideration of the following loads has been taken into account for the PCCS condenser:

- D (+B) Dead Weight (+ Buoyancy)
- P_t Test Pressure
- P_a Design accident pressure generated by a LOCA
- T_t Thermal effects during tests
- T_a Thermal effects generated by a LOCA
- SSE Safe Shutdown Earthquake
- SRVD Safety Relief Valve Discharge
- LOCA Loss of Coolant Accident

A.3 Load Combinations

Enveloping Load Combinations are described in Table A-1.

Table A-1: PCCS Load Combinations

Service Level (elastic analysis)	Load Combination
Test Condition	$D + P_t + T_t$
Design Condition	$D + P_a + T_a$
Levels A, B	$D + P_a + T_a + SRV + LOCA$
Levels C, D	$D + P_a + T_a + SSE + SRV + LOCA$

A.4 Finite Element Model Inputs

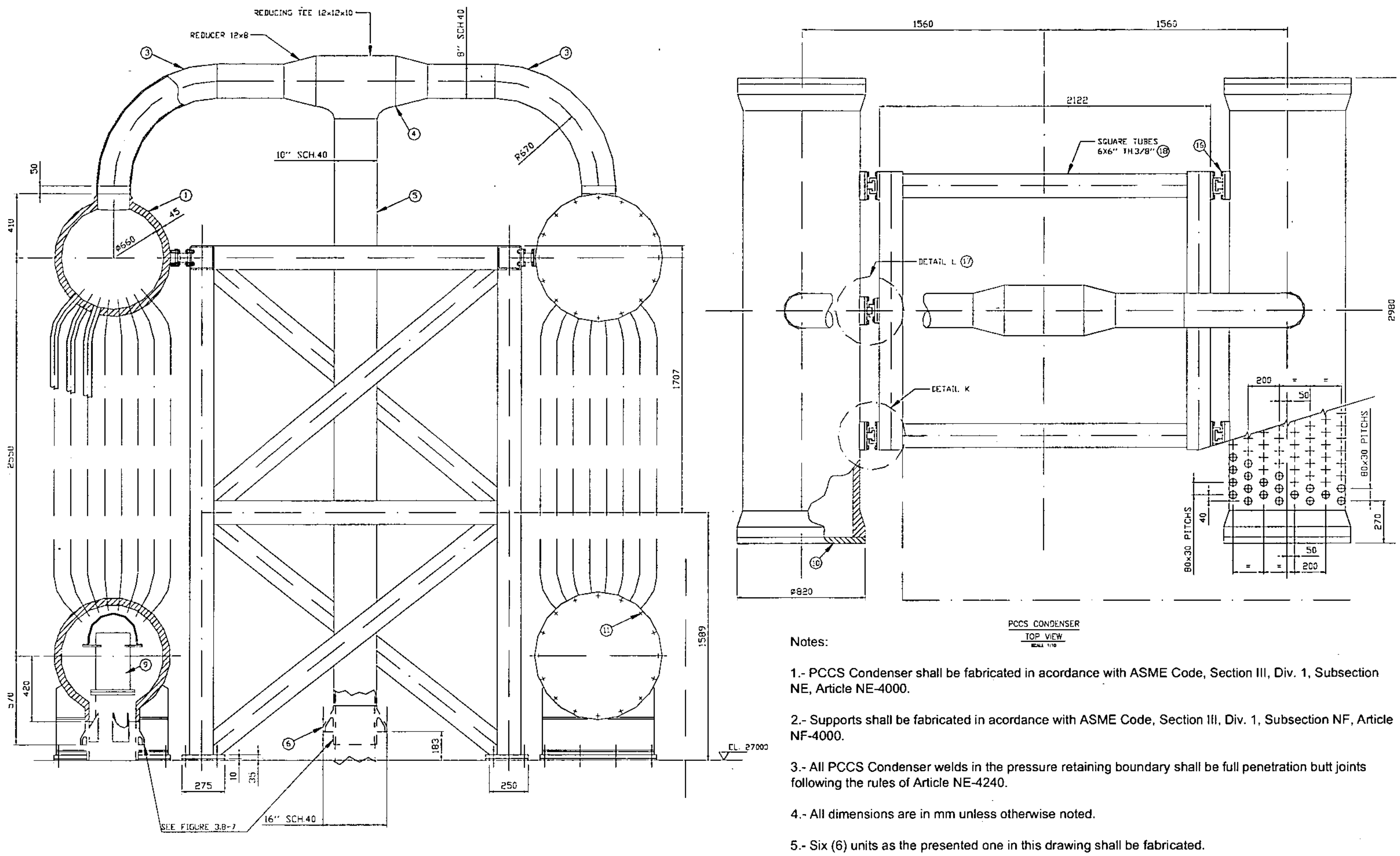
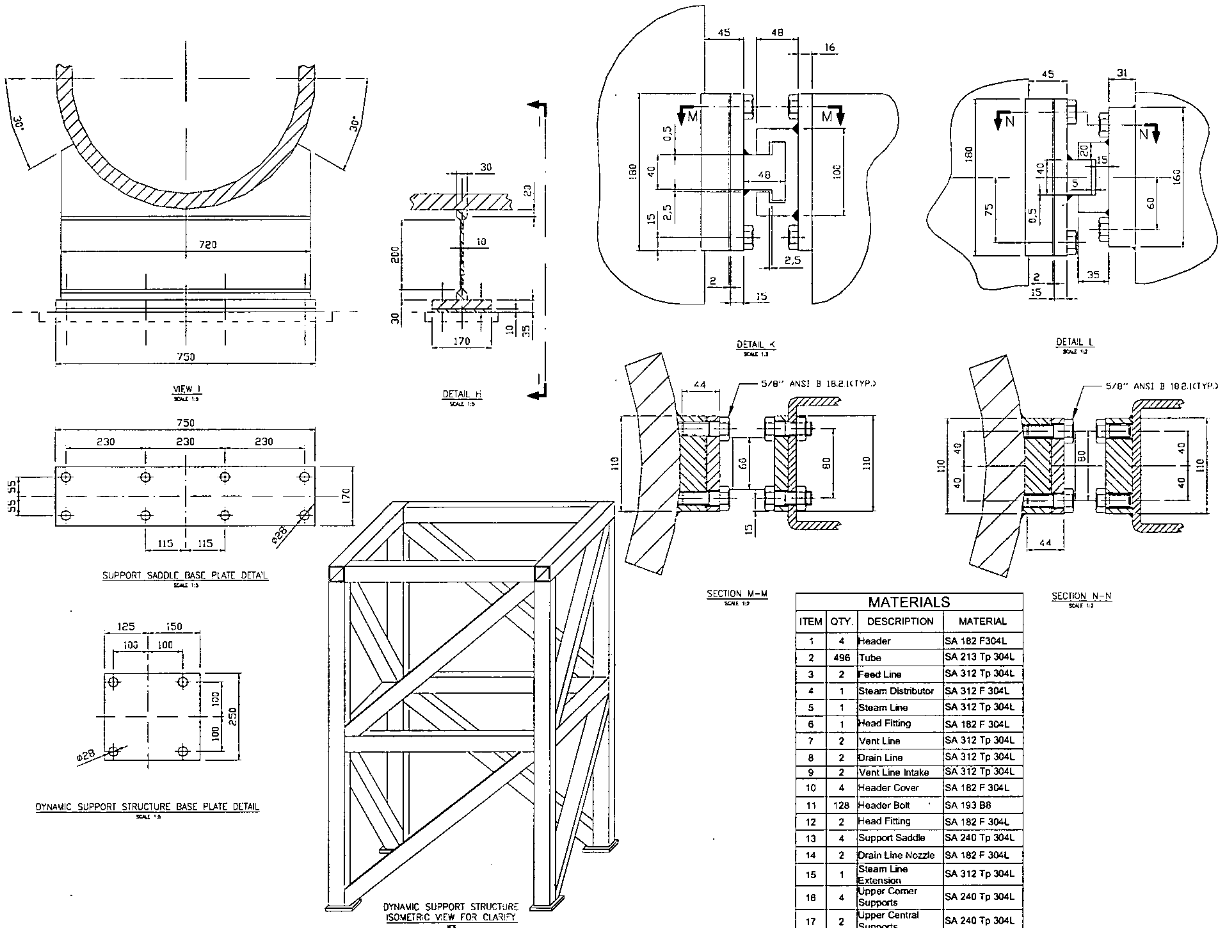


Figure A.1-1a: PCCS Condenser and Supports



MATERIALS			
ITEM	QTY.	DESCRIPTION	MATERIAL
1	4	Header	SA 182 F304L
2	496	Tube	SA 213 Tp 304L
3	2	Feed Line	SA 312 Tp 304L
4	1	Steam Distributor	SA 312 F 304L
5	1	Steam Line	SA 312 Tp 304L
6	1	Head Fitting	SA 182 F 304L
7	2	Vent Line	SA 312 Tp 304L
8	2	Drain Line	SA 312 Tp 304L
9	2	Vent Line Intake	SA 312 Tp 304L
10	4	Header Cover	SA 182 F 304L
11	128	Header Bolt	SA 193 B8
12	2	Head Fitting	SA 182 F 304L
13	4	Support Saddle	SA 240 Tp 304L
14	2	Drain Line Nozzle	SA 182 F 304L
15	1	Steam Line Extension	SA 312 Tp 304L
16	4	Upper Corner Supports	SA 240 Tp 304L
17	2	Upper Central Supports	SA 240 Tp 304L
18	20	Square Tubes	SA 479 Tp 304L

Figure A.1-1b: PCCS Condenser and Supports Details

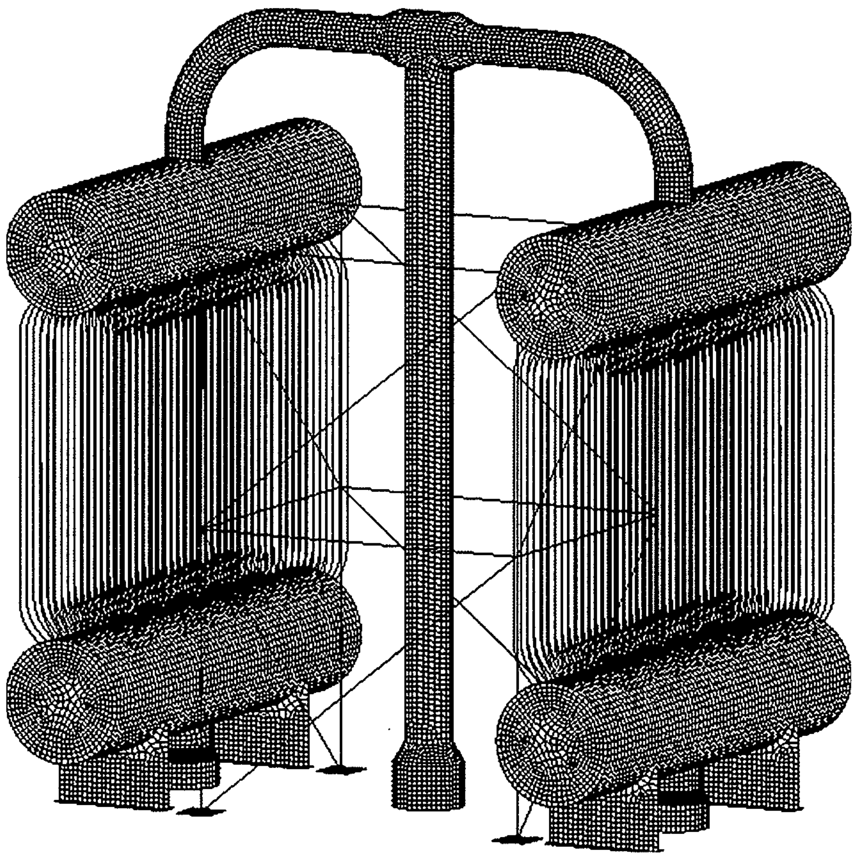


Figure A.1-2: FEM of PCCS Condenser and Supports

A.5 Stress Results and Margin to Allowable

Table A-2: Stress Summary of the PCCS condenser and Supports

Component	Stress Category	*Test*			*Design*			*Service Level A/B*			*Service Level C/D*		
		Calculated Stress (MPa)	**Allowable Stress (MPa)**	**Stress Margin (%)**	**Calculated Stress (MPa)**	**Allowable Stress (MPa)**	**Stress Margin (%)**	**Calculated Stress (MPa)**	**Allowable Stress(1) (MPa)**	**Stress Margin (%)**	**Calculated Stress (MPa)**	**Allowable Stress(2) (MPa)**	**Stress Margin (%)**
Upper Header	P_m	11.8	119.8	90	11.8	114.9	90	16.8	114.9	85	37.8	137.9	73
	$P_L + P_b$	11.8	183.7	94	11.8	150.6	92	16.8	150.6	89	39.8	180.7	78
Lower Header	P_m	11.8	119.8	90	11.8	114.9	90	24.8	114.9	78	47.8	137.9	65
	$P_L + P_b$	11.8	183.7	94	11.8	150.6	92	26.8	150.6	82	55.8	180.7	69
Tubes	P_m	11.4	119.8	91	11.4	114.9	90	15.4	114.9	87	19.4	137.9	86
	$P_L + P_b$	11.4	183.7	94	11.4	150.6	92	33.4	150.6	78	66.4	180.7	63
Feed Line	P_m	9.9	119.8	92	9.9	114.9	91	23.9	114.9	79	79.9	137.9	42
	$P_L + P_b$	9.9	183.7	95	9.9	150.6	93	29.9	150.6	80	110.9	180.7	39
Steam line	P_m	10.9	119.8	91	10.9	114.9	91	25.9	114.9	77	80.9	137.9	41
	$P_L + P_b$	10.9	183.7	94	10.9	150.6	93	31.9	150.6	79	112.9	180.7	38
Steam Distributor	P_m	12.6	119.8	89	12.6	114.9	89	24.6	114.9	79	67.6	137.9	51
	$P_L + P_b$	12.6	183.7	93	12.6	150.6	92	26.6	150.6	82	73.6	180.7	59
Condensate Lines	P_m	12.6	119.8	89	12.6	114.9	89	31.6	114.9	73	66.6	137.9	52
	$P_L + P_b$	12.6	183.7	93	12.6	150.6	92	37.6	150.6	75	80.6	180.7	55
Header Cover	P_m	87.0	119.8	27	87.0	114.9	24	89.0	114.9	23	92.0	114.9	20
	$P_L + P_b$	87.0	183.7	53	87.0	150.6	42	89.0	150.6	41	92.0	180.7	49
Header Bolt	Average Stress	70.3	144.7	51	70.3	110.1	36	70.3	220.2	68	70.3	220.2	68
Support Saddle	P_m	Negligible						29.0	112.6	74	87.0	168.9	48
	$P_L + P_b$							30.0	168.9	82	88.0	253.4	65
	Shear							9.0	67.6	87	26.0	101.3	74
Truss Support Structure	Tension							14.0	76.6	82	69.0	114.9	40
	Shear							3.0	51.1	94	12.0	76.6	84
	Compression							14.0	47.9	71	69.0	71.9	4
	Bending							14.0	84.3	83	70.0	126.4	45

1) Allowable stress values correspond to Level A

2) Allowable stress values correspond to Level C

APPENDIX B - PCCS STRUCTURAL ANALYSIS WITH DETONATOIN LOADING

B.1 Modifications for Analysis of PCCS Condenser

The purpose of this Appendix is to describe the work that will be done to augment the analysis described in Appendix A to include loads for detonation. A preliminary sizing estimate has been performed in this report to assess the need for changes in the design of the PCCS condenser to account for detonation loads. As a result, the analysis described in Appendix A shall be redone with the inputs modified as follows:

- The tube material for the PCCS is changed from 304L Stainless Steel to SA-312 TPXM-19.
- Tube thickness is increased to [[ ]] (OD remains the same)
- Number of tubes increased from [[ ]] per module to [[ ]] per module.
- Length of drums increased to accommodate additional tubes
- Supporting structure changed to have 40% margin.
- A Detonation load (DET) is added to the load definitions consistent with this report and as shown in the load combination Table B-1.
- The DET load shall be applied statically using a pressure of 19.3 MPa with DLF for the tubes and lower drum as given in Table 3-3.
- Two separate analyses for DET shall be analyzed with 1) a detonation in one tube and 2) a detonation in the lower drum.

Also, a separate model will be created to assess the detonation loads on the condenser tubes. The model described in Appendix A used [[ ]] elements for the tubes, which is adequate for a seismic and hydrodynamic analysis, but not for detonation loads. The detonation analysis may use [[ ]] elements to model the tubes and their interface with the drums.

Table B-1: Modified PCCS Load Combinations

Service Level (elastic analysis)	Load Combination
Test Condition	$D + P_t + T_t$
Design Condition	$D + P_a + T_a$
Levels A, B	$D + P_a + T_a$ + SRV + LOCA
Level C	$D + P_a + T_a$ + SSE + SRV + LOCA
Level D	$D + P_a + T_a$ + SSE + SRV + LOCA D + DET + T_a + SSE

Enclosure 6

MFN 10-044 Revision 1

Response to Portion of NRC Request for

Additional Information Letter No. 406

Related to ESBWR Design Certification Application

Engineered Safety Features

RAI Number 6.2- 202

Affidavit

GE-Hitachi Nuclear Energy Americas LLC

AFFIDAVIT

I, David H. Hinds, state as follows:

(1) I am the Manager, New Units Engineering, GE Hitachi Nuclear Energy ("GEH"), and have been delegated the function of reviewing the information described in paragraph (2) which is sought to be withheld, and have been authorized to apply for its withholding.

(2) The information sought to be withheld is contained in enclosures 1 and 4 of GEH's letter, MFN 10-044 Revision 1, Mr. Richard E. Kingston to U.S. Nuclear Energy Commission, entitled "*Response to Portion of NRC Request for Additional Information Letter No. 406 – Related to ESBWR Design Certification Application – Engineered Safety Features – RAI Number 6.2-202,*" dated March 23, 2010. The proprietary information in enclosure 1, which is entitled "*MFN 10-044 Revision 1 – Response to Portion of NRC Request for Additional Information Letter No. 406 – Related to ESBWR Design Certification Application – Engineered Safety Features – RAI Number 6.2-202 – GEH Proprietary Information,*" and enclosure 4, which is entitled "*MFN 10-044 Revision 1 – Response to Portion of NRC Request for Additional Information Letter No. 406 – Related to ESBWR Design Certification Application – Engineered Safety Features – RAI Number 6.2-202 – NEDE-33572 Revision 0, "ESBWR PCCS Condenser Structural Evaluation," March 2010, GEH Proprietary Information,*" is indicated as the content contained between opening double brackets ([[) and closing double brackets (]]), and underlined. [[This sentence is an example {3}]]. Figures and large equation objects are identified with double square brackets before and after the object. In each case, the superscript notation {3} refers to Paragraph (3) of this affidavit, which provides the basis for the proprietary determination.

(3) In making this application for withholding of proprietary information of which it is the owner or licensee, GEH relies upon the exemption from disclosure set forth in the Freedom of Information Act ("FOIA"), 5 USC Sec. 552(b)(4), and the Trade Secrets Act, 18 USC Sec. 1905, and NRC regulations 10 CFR 9.17(a)(4), and 2.390(a)(4) for "trade secrets" (Exemption 4). The material for which exemption from disclosure is here sought also qualify under the narrower definition of "trade secret", within the meanings assigned to those terms for purposes of FOIA Exemption 4 in, respectively, Critical Mass Energy Project v. Nuclear Regulatory Commission, 975F2d871 (DC Cir. 1992), and Public Citizen Health Research Group v. FDA, 704F2d1280 (DC Cir. 1983).

(4) Some examples of categories of information which fit into the definition of proprietary information are:

a. Information that discloses a process, method, or apparatus, including supporting data and analyses, where prevention of its use by GEH's competitors without license from GEH constitutes a competitive economic advantage over other companies;

b. Information which, if used by a competitor, would reduce his expenditure of resources or improve his competitive position in the design, manufacture, shipment, installation, assurance of quality, or licensing of a similar product;

c. Information which reveals aspects of past, present, or future GEH customer-funded development plans and programs, resulting in potential products to GEH;

d. Information which discloses patentable subject matter for which it may be desirable to obtain patent protection.

The information sought to be withheld is considered to be proprietary for the reasons set forth in paragraphs (4)a. and (4)b. above.

(5) To address 10 CFR 2.390(b)(4), the information sought to be withheld is being submitted to NRC in confidence. The information is of a sort customarily held in confidence by GEH, and is in fact so held. The information sought to be withheld has, to the best of my knowledge and belief, consistently been held in confidence by GEH, no public disclosure has been made, and it is not available in public sources. All disclosures to third parties, including any required transmittals to NRC, have been made, or must be made, pursuant to regulatory provisions or proprietary agreements which provide for maintenance of the information in confidence. Its initial designation as proprietary information, and the subsequent steps taken to prevent its unauthorized disclosure, are as set forth in paragraphs (6) and (7) following.

(6) Initial approval of proprietary treatment of a document is made by the manager of the originating component, the person most likely to be acquainted with the value and sensitivity of the information in relation to industry knowledge, or subject to the terms under which it was licensed to GEH. Access to such documents within GEH is limited on a "need to know" basis.

(7) The procedure for approval of external release of such a document typically requires review by the staff manager, project manager, principal scientist, or other equivalent authority for technical content, competitive effect, and determination of the accuracy of the proprietary designation. Disclosures outside GEH are limited to regulatory bodies, customers, and potential customers, and their agents, suppliers, and licensees, and others with a legitimate need for the information, and then only in accordance with appropriate regulatory provisions or proprietary agreements.

(8) The information identified in paragraph (2) is classified as proprietary because it contains details of GEH's design and licensing methodology. The development of the methods used in these analyses, along with the testing, development and approval of the supporting methodology was achieved at a significant cost to GEH.

(9) Public disclosure of the information sought to be withheld is likely to cause substantial harm to GEH's competitive position and foreclose or reduce the availability of profit-making opportunities. The information is part of GEH's comprehensive BWR safety and technology base, and its commercial value extends beyond the original development cost. The value of the technology base goes beyond the extensive physical database and analytical methodology and includes development of the expertise to determine and apply the appropriate evaluation process. In addition, the technology base includes the value derived from providing analyses done with NRC-approved methods.

The research, development, engineering, analytical and NRC review costs comprise a substantial investment of time and money by GEH.

The precise value of the expertise to devise an evaluation process and apply the correct analytical methodology is difficult to quantify, but it clearly is substantial.

GEH's competitive advantage will be lost if its competitors are able to use the results of the GEH experience to normalize or verify their own process or if they are able to claim an equivalent understanding by demonstrating that they can arrive at the same or similar conclusions.

The value of this information to GEH would be lost if the information were disclosed to the public. Making such information available to competitors without their having been required to undertake a similar expenditure of resources would unfairly provide competitors with a windfall, and deprive GEH of the opportunity to exercise its competitive advantage to seek an adequate return on its large investment in developing and obtaining these very valuable analytical tools.

I declare under penalty of perjury that the foregoing affidavit and the matters stated therein are true and correct to the best of my knowledge, information, and belief.

Executed on this 23rd day of March 2010.

David H. Hinds
GE-Hitachi Nuclear Energy Americas LLC