Primary Evaluation Number EE-46-0007 - REV.B

ENGINEERING EVALUATION OF PRESTRESSED CONCRETE REACTOR VESSEL AND CORE SUPPORT FLOOR STRUCTURES FOR A PROPOSED SYSTEM 46 TEMPERATURE CHANGE

Prepared by: Edmund Julius 9/27/91
DATE

Verified by: Aldrin Ricken 9-27-91
DATE

Approved by: Martin Beale 10/1/91
DEPARTMENT MANAGER DATE

9110290014 911011
PDR ADOCK 05000267
P PDR

1.0 PURPOSE

This Engineering Evaluation (EE) will determine the feasibility of allowing a decrease in the operating temperatures of System 46 cooling water provided to the Prestressed Concrete Reactor Vessel (PCRV) and the Core Support Floor (CSF). Specifically, this EE will investigate the possibility of allowing the minimum average of the inlet and outlet cooling water temperature to decrease from the 100°F specified in LCO 4.2.15 (e) to 85°F. This change is desirable because of present System 46 operating considerations.

2.0 SUMMARY

Various areas of the PCRV and CSF judged to be the most critical were investigated to determine the effects of the proposed System 46 operating temperature change. Areas investigated were the PCRV liner, the PCRV liner anchor studs, the PCRV concrete, the PCRV penetrations, the PCRV tendons, the PCRV reinforcing rods, the CSF liner, the CSF concrete, and the CSF reinforcing rods.

The analyses performed to evaluate these various areas conservatively assumed that the proposed 15°F temperature change occurs instantly in the item being investigated. This assumption provides conservative results as it creates the maximum differential thermal movement between adjacent items which are physically bonded, such as for example, the PCRV liner and concrete which are connected together by anchor studs embedded in the concrete and welded to the liner. The assumption of instantaneous temperature change is very conservative as the thermal masses involved are very large and temperature variations of the System 46 cooling water tend to occur slowly.

The stress levels in the various items due to the 15°F temperature change were found to be relatively low even when based upon very conservative assumptions. This is due to the fact that the proposed temperature variation of 15°F is very low and does not result in high levels of stress in even completely restrained structures. The total stress levels in the PCRV and CSF structures due to the proposed temperature change and other previously analyzed loads were found to be acceptable. A summary of the stress levels in the areas investigated follows.

SUMMARY OF PCRV AND CSF STRESSES DUE TO 15°F SYSTEM 46 TEMPERATURE CHANGE

PCRV LINER	STRESS INTENSITY (PSI)	STRESS ALLOWABLE (PSI)
LOWER FLOOR COLUMN ANCHOR - LOCAL STRESS INTENSITY IN LINER	22,539	34,600
JUNCTION WITH BOTTOM ACCESS PENETRATION LINER - STRESS INTENSITY IN CAVITY LINER	24,039	65,700

PCRV LINER ANCHOR STUDS	MAXIMUM SHEAR LOAD	ALLOWABLE SHEAR LOAD
	18,605 LB.	32,500 LB.

PCRV CONCRETE	MAXIMUM TENSILE STRESS (PSI)	ALLOWABLE TENSILE STRESS (PSI) (See Note 1)
	220	233

PCRV PENETRATIONS	STRESS INTENSITY (PSI)	STRESS LIMIT (PSI)
BOTTOM ACCESS PENETRATION	PRIMARY 40,534 SECONDARY 41,318	69,300 52,500
HELIUM CIRCULATOR PENETRATION	PRIMARY 36,024 SECONDARY 36,722	52,500 52,500
REFUELING PENETRATION	PRIMARY 19,419 SECONDARY 34,079	52,500 52,500
TOP ACCESS PENETRATIONS	PRIMARY 41,879 SECONDARY 30,589	69,300 52,500

PCRV TENDONS	The stress levels in the tendons do not increase due to this proposed temperature change.
PCRV REINFORCING RODS	The stress levels in the reinforcing rods do not increase due to the proposed temperature change.

CSF LINER	STRESS (PSI)	STRESS ALLOWABLE (PSI)
Liner - maximum tensile stress	6,639	23,100
Liner - support column junction	62,539	69,300

CSF CONCRETE	MAXIMUM TENSILE STRESS (PSI)	ALLOWABLE TENSILE STRESS (PSI) (See Note 1)
	382	233

CSF REINFORCING RODS	The stress levels in the reinforcing rods do not increase due to this proposed temperature change.

NOTE 1: The 233 PSI allowable is for unreinforced concrete. The PCRV and CSF are constructed with bonded reinforcing steel and this low tensile stress is not significant.

The effects of the lower temperature upon the ability of the PCRV liner materials to resist fracture were investigated. The PCRV liner is subjected to neutron irradiation with the top head liner receiving the highest dose. This irradiation tends to increase the Nil Ductility Transition (NDT) temperature of the steel liner. LCO 4.2.15 specifies a minimum liner temperature of 100°F so as to maintain a 60°F margin above the NDT at the plant end-of-life after 30 years of operation.

The reactor was permanently shut down on August 18, 1989 having accumulated 890 Effective Full Power Days, which represents approximately one-tenth of the design lifetime and which corresponds to a maximum integrated neutron dose of 2.4E E17 n/cm^3. This neutron exposure would cause a shift in the NDT temperature of approximately one-tenth of the experimentally determined NDT temperature shifts.

The fracture transition elastic (FTE) temperature is approximately NDT + 60°F and this is the lowest allowable temperature. The end-of-life FTEs were calculated to be 10°F for the liner material and -2°F for the liner weldment material. These FTE temperatures are well below the proposed value of 85°F and it was concluded that operation at 85°F is acceptable for the liner materials.

3.0 SCOPE

The scope of this EE includes the structural evaluation of the PCRV and CSF for loads imposed by the proposed temperature change. Additionally, the scope of this EE includes the fracture mechanics evaluation of the PCRV liner for the proposed decrease in liner temperature.

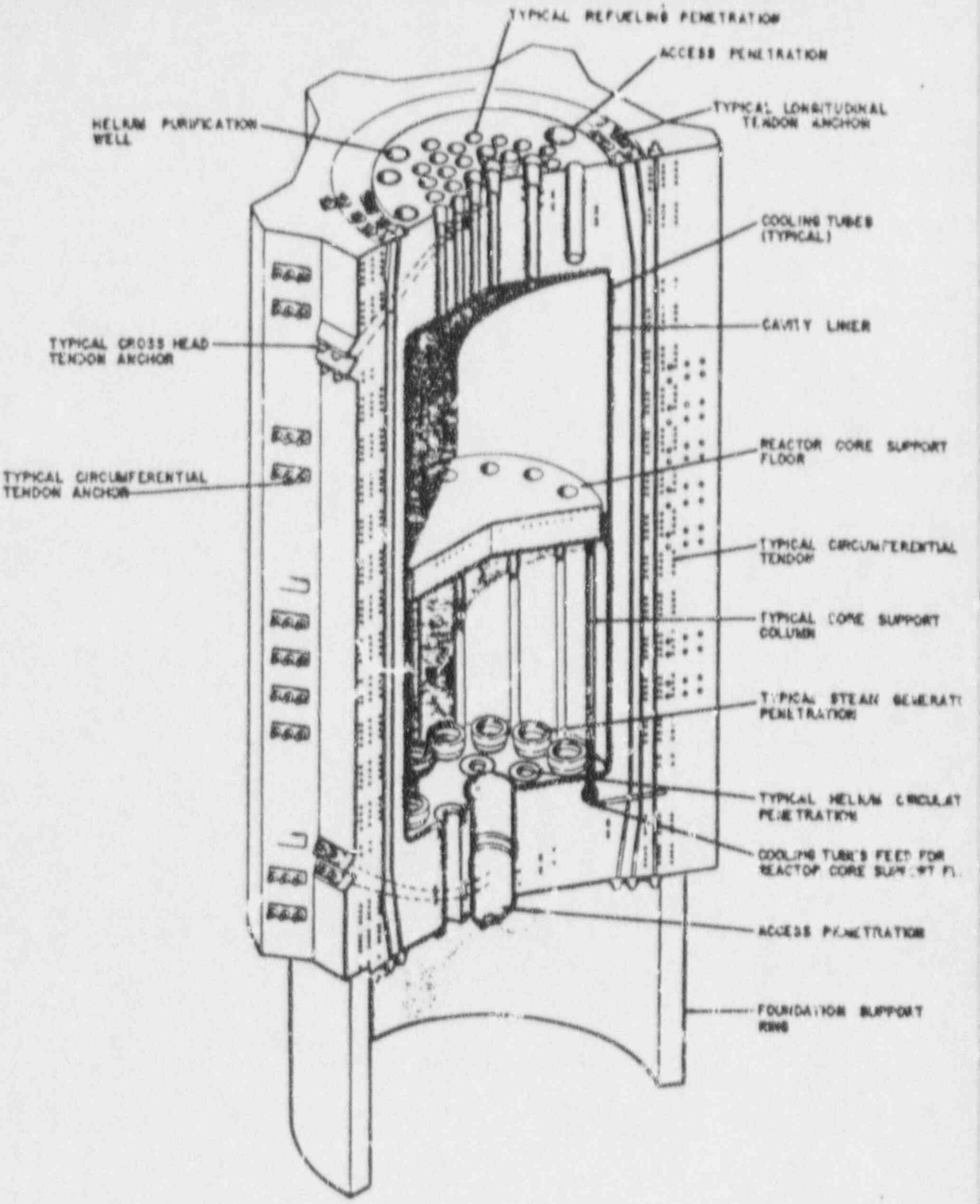


Figure 4.1 PCRV General Configuration

R1101-100C

4.0 BACKGROUND

The Prestressed Concrete Reactor Vessel (PCRV) is the structure that contains the reactor core and the entire primary coolant system. It functions as the primary coolant pressure boundary. The general configuration of the PCRV is shown in Figure 4.1.

The PCRV is constructed of high strength concrete reinforced with bonded reinforcing steel and prestressed by means of the post-tension method with steel tendons. The main cavity of the PCRV is an upright circular cylinder 31 ft. in diameter and 75 ft. high. The exterior vertical surface approximates a hexagonal prism with vertical pilasters at each corner which accommodate anchors for circumferential prestressing tendons. Both PCRV heads are flat. The external PCRV dimensions are 49 ft. across the flats of the hexagon and 106 ft. high. The wall and heads are 9 ft. and 15 ft. 6 in. thick, respectively.

The concrete walls and heads are constructed around a 3/4 inch thick carbon steel liner which provides a leak-tight membrane for containing the primary coolant within the PCRV cavity. This liner is anchored to the concrete by means of studs welded to the liner and embedded in the concrete.

Prestressing tendons, located in conduits embedded in the concrete, are used to prestress the entire structure prior to pressurization. Prestressing forces are oriented such that they oppose internal pressure.

The concrete is reinforced with bonded reinforcing steel which provides the added tensile strength needed where discontinuities cause unavoidable secondary tensile strain, distributes and minimizes width and depth of the minor cracking caused by concrete shrinkage and tensile strain from thermal gradients, and resists localized high compressive and shear stresses that would otherwise overload the concrete.

The concrete, reinforcing steel, prestressing system, and steel liner function as a composite structure.

The temperature of the PCRV concrete is controlled by means of insulation mounted on the inside surface of the liner, and cooling tubes welded to the concrete side of the liner.

In general the cooling tubes are spaced on approximately 7.5 in. centers. However, additional cooling system capacity is provided in the cylindrical section of the PCRV liner from just below the core support floor to just above the top of the core barrel. Here the spacing is 3.75 in. Maximum spacing of cooling tubes on the top head liner is 3 in. Cooling tubes are arranged so that alternate tubes are connected to redundant supply and return headers.

The whole of the internal surface of the liner is covered by the thermal barrier which uses Kaowool insulation, a ceramic fiber blanket material of high chemical purity. The blankets are compressed against the PCRV liner by 1/4 in. carbon steel cover plates and studs that are attached to the liner. This causes Kaowool to conform very closely to liner surface irregularities and provides an effective seal against helium flowing in those irregularities, thus preventing heat transfer to the liner by forced or natural convection.

Due to operational considerations it is desirable to reduce the operating temperature of System 46 which provides cooling water for the PCRV and the CSF. The Technical Specifications LCO 4.2.15 establishes the following limits for System 46 operating temperatures:

a) The maximum temperature difference between the outlet water temperature of the PCRV cooling water system, and the PCRV external concrete surface temperature, averaged over 24 hours, shall not exceed 50°F.

b) The maximum outlet water temperature of the PCRV cooling water system shall not exceed 120°F.

c) The maximum temperature difference between the outlet water temperature and the inlet water temperature of the PCRV cooling water system shall not exceed 20°F.

d) The maximum rate of change of the PCRV concrete temperature shall not exceed 14°F per week, as indicated by the weekly average outlet water temperature of the PCRV cooling water system.

e) The minimum average of the inlet and outlet cooling water temperatures shall be greater than or equal to 100°F.

This Engineering Evaluation will investigate the effects of lowering the average of the inlet and outlet temperatures from 100°F (condition "e" above) to 85°F. This would provide the additional working margin desired for System 46 operating considerations. Additionally, the maximum outlet water temperature will be lowered from 120°F to 105°F (condition "b" above). No changes are proposed for the other conditions (a, c and d above).

The average of the inlet and outlet cooling water temperatures is presently approximately 107°F. The PCRV internal pressure is limited to less than 1 psig by the requirements of LCO 4.7.1, but a maximum credible pressure of 5 psig was assumed for this analysis per section 9.5.5 of Ref. 8.1.

It is of interest to note that the proposed System 46 operating temperature change can be viewed as being very close to a previously analyzed condition. Consider Table 5.3-2 of Ref. 8.1. Here are reported some of the stress results for a variety of loading conditions which cover the life of the plant. Of interest are the following cases: 1) the PCRV prestressed, unheated (70°F), and at atmospheric pressure 2) the PCRV prestressed, at design temperature, and at atmospheric pressure 3) the PCRV at the end of operation, at design temperature, and at reference pressure, and 4) the PCRV at the end of operation, unheated, and at atmospheric pressure. These cases contain the history of the PCRV as it was prestressed, heated, pressurized, depressurized, and allowed to cool to atmospheric temperature.

The proposed loading case is very close to case 4 mentioned above with the primary differences being that the PCRV will not have cooled completely down to the case 4 level and the fact that it is possible that the PCRV could be pressurized to a low level (5 PSI per Ref. 8.1) versus atmospheric pressure of case 4. The PCRV also has not been pressurized for as long as was assumed in case 4 resulting in less of a loss of prestress in the concrete and tendons due to concrete creep than was predicted in the case 4 analysis.

5.0 APPROACH

The PCRV and CSF structures were previously analyzed for a variety of load cases and were found to be structurally adequate as reported in Ref. 8.1. The evaluation of this EE builds upon the results of the previous analyses.

Stresses which could arise due to the proposed temperature change are conservatively calculated for various PCRV and CSF components which are considered to be the most critical. In general the assumption is made that the temperature change is instantaneous, resulting in the maximum differential thermal movements and corresponding thermal stresses. These stresses are added to previously calculated stresses in a conservative manner and the total stress is compared to the allowable stress.

The PCRV liner is subjected to neutron irradiation during plant operation. Calculations are performed to determine the Nil Ductility Temperature of the liner materials based upon actual plant operating history. The new NDT values are compared to the proposed reduced liner temperature of 85°F to ensure that a 60°F margin exists between the NDT and the minimum liner temperature.

6.0 EVALUATION OF PCRV AND CSF STRUCTURES

6.1 PCRV Liner

The whole of the internal surface of the PCRV, that is exposed to primary coolant, is covered by a continuous 3/4 inch thick carbon steel liner. Welded studs are attached to the outside surface of the liner on a 7-1/2 in. × 7-1/2 in. pitch and are embedded in the PCRV concrete. The liner, studs, and PCRV concrete act as a composite structure and the liner follows the major concrete strains. (Ref. 8.1, Section 5.7)

During the proposed System 46 operating temperature change it is possible that the liner would be subjected to some thermally induced stresses. These stresses would occur due to the differential thermal growth of the liner relative to the PCRV concrete which would be restrained by the anchor bolts.

For a limiting case the liner will be assumed to instantly cool off the entire proposed decrease of 15°F from the conditions of LCO 4.2.15 (e) while the concrete remains at the initial temperature. The liner will then be conservatively treated as a uniform flat plate held at the edges subjected to a uniform temperature decrease of 15°F. Such a plate would attempt to contract and, being restrained, would develop tensile stresses. The worst case magnitude of these tensile stresses can be calculated as follows:

$$\sigma = \frac{\Delta T\, \alpha\, E}{\left(1 - \mu\right)}$$ (Ref. 8.3, Pg. 374, Article 88, Case 2)

$\Delta T = 15°F$

$\alpha = Coefficient\ of\ thermal\ expansion$

$= 6.5 \times 10^{-6}\ In/In - °F$

$E = modulus\ of\ elasticity\ 29 \times 10^{6}\ PSI$ (Ref. 8.4, Pg. 4)

$\mu = Poissons\ Ratio = 0.3$

$$\sigma = \frac{\left(15°F\right)\left(6.5 \times 10^{-6}\ In/In - °F\right)\left(29 \times 10^{6} Lb/In^{2}\right)}{\left(1 - .3\right)}$$

$\sigma = 4,039\ PSI\ (Tension)$

The liner is in general in a state of compressive stress for all plant operating conditions due to the prestress of the PCRV tendons. The level of compressive stress in the liner is increased when, as in the case being considered, the internal pressure of the PCRV is decreased (Refer to Ref. 8.1, Table 5.3-2 for various load case liner stresses). The liner tensile stresses calculated above will tend to negate a portion of these compressive stresses which exist in the bulk of the liner. This fact will be conservatively neglected and the calculated liner tensile stresses will be added directly to the liner stresses as reported in Table 5.7-1 of Ref. 8.1. It is also noted that the calculated thermal stress is secondary in nature but will be conservatively added to certain primary stresses reported in Table 5.7-1.

Area	Stress Intensity (PSI)	Stress Allowable (PSI)
Lower floor column anchor - local stress intensity in liner	18,500 + 4,039 = 22,539	34,600
Junction with bottom access penetration liner - stress intensity in cavity liner	20,000 + 4,039 = 24,039	65,700
Junction with core support column - stress intensity in cavity liner	24,800 + 4,039 = 28,839	69,300
Junction with top access penetration - liner - stress intensity in cavity liner	55,900 + 4,039 = 59,939	65,700

It is concluded that the PCRV liner is structurally adequate for loads imposed by the proposed System 46 operating temperature decrease.

6.2 PCRV Liner Anchor Studs

The liner anchor studs are attached to the outside surface of the liner on a 7½ inch circumferential by 7½ inch axial pitch (Ref. 8.1, Section 5.7.1). The anchor studs act as shear anchors which force the liner and PCRV concrete to act as a composite structure.

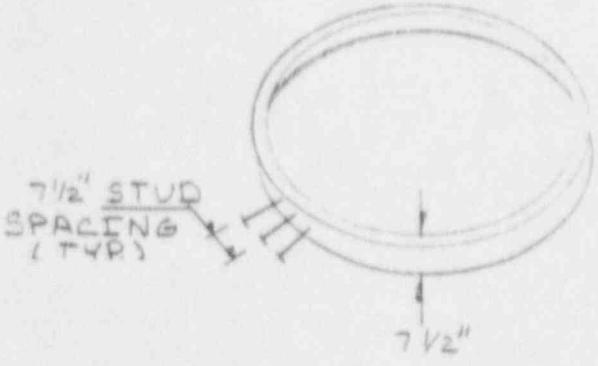
The proposed reduction in the System 46 operating temperatures could potentially increase the loads acting upon the anchor studs by two mechanisms. The first mechanism is due to the fact that when the liner cools off it will shrink circumferentially and attempt to move in the inward radial direction away from the PCRV concrete. This radial movement will be resisted by the anchor studs resulting in a tensile axial force in the studs. The second mechanism is due to axial shrinkage of the liner which could result in shear forces acting upon the studs as discussed below.

The worst case scenario for both of the mechanisms is that the liner instantly cools off the full postulated 15°F. This will maximize the differential thermal movement between the PCRV concrete and liner and consequently maximize the forces acting upon the anchor studs which resist these differential movements.

The axial tensile forces acting upon the anchor studs due to circumferential thermal shrinkage of the liner will be conservatively calculated as follows:

Since the studs are located on a 7½ × 7½ inch pitch, in order to calculate the loads on a circumferential row of anchor studs the liner can be treated as a

$7\frac{1}{2}$" high section of the liner (ring) which is assumed to be subjected to a 15°F temperature drop.



The unrestrained thermal contraction of this ring is then:

$$\delta = \alpha \Delta T D$$ (Ref. 8.5, Pg. 82)

where

δ = *calculated change in diameter*

α = *coefficient of thermal expansion*

$= 6.5 \times 10^{-6}\ in/in - {}^{\circ}F$ Ref. 8.4, Pg. 4

$\Delta T = 15^{\circ}F$ *(Assumed)*

D = *Liner Diameter* $= 31' = 31 \times 12 = 372"$ (Ref. 8.1, Section 5.1)

$$\delta = \left(6.5 \times 10^{-6}\right)\left(15\right)\left(372\right) = 0.0363"$$

The radial pressure acting upon the ring to produce this deflection will now be calculated. The pressure will then be multiplied by the effective contributory area of $7\frac{1}{2} \times 7\frac{1}{2}$ inches per stud. This will give the axial force acting on each stud.

$$Radial\,Displacement = \frac{RPR}{Et} = \delta$$ (Ref. 8.3, Pg. 298. Case 1)

solving for P:

$$P = \frac{\delta E t}{R^2}$$

where

R = Radius = $(31 \times 12)(1/2) = 186''$ (Ref. 8.1, Section 5.1)

P = Pressure (To be calculated)

E = Modulus of Elasticity
= 29×10^6 PSI (Ref. 8.4, Pg. 4)

t = $3/4''$ (Ref. 8.1, Section 5.7.1)

Radial Displacement = 1/2 diameter change calculated above
= $(1/2)(.0363)'' = 0.0181''$

$$P = \frac{\left(0.0181\right)\left(29 \times 10^6\right)\left(0.75\right)}{\left(186^2\right)} = 11.4\,PSI$$

Radial Load/Stud = Area × Pressure = $(7\frac{1}{2}'' \times 7\frac{1}{2}'')(11.4\,PSI) = 641$ Lb.

The resulting stress in the 3/4 inch diameter studs from this load is

$$\sigma = P/A = \left(641\,Lb\right)/\left(1/4\right)\left(\pi\right)\left(3/4^2\right)$$

$$= 1{,}450\,PSI$$

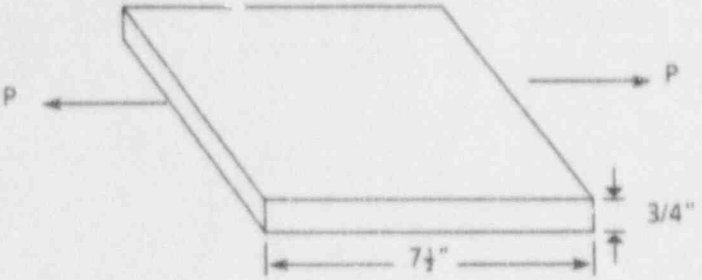
For the liner stud spacing and embedment lengths the stud strength will be fully developed and the stud will fail before the concrete. The above calculated stud axial stress is very low and is evaluated as being acceptable. No other axial stresses were reported in Ref. 8.1 and the axial/shear interaction is evaluated as being acceptable based on the shear force margins calculated below.

The second mechanism to be discussed is the axial thermal shrinkage of the liner. Due to the general symmetry of the stud placements, the net shear force on a given stud due to this shrinkage will be close to zero due to the fact that there will be two equal and opposing forces acting at the stud.

For the purposes of this evaluation it will be conservatively assumed that the shear forces are not balanced but are reacted by the studs.

This postulated condition will be modeled as a section of liner plate $7\frac{1}{2}'' \times 7\frac{1}{2}''$ with two opposite edges anchored and subjected to a 15°F temperature drop.

The force required to resist the shrinkage will be calculated and will be that assumed to be acting upon the studs.



$$\delta = \frac{PL}{AE} = \alpha \Delta T L$$

$$P = \alpha \Delta T A E$$

$$P = \left(6.5 \times 10^{-6}\right)\left(15\right)\left(7\tfrac{1}{2} \times 3/4\right)\left(29 \times 10^{6}\right)$$

$$= 15{,}905\ LB$$

This very conservative shear force will be added to the previously calculated Ref. 8.1 maximum shear force and compared to the allowable.

Previous maximum shear load = 2,700 LB (Ref. 8.1, Table 5.7-1)

Allowable = 32,500 LB (Ref. 8.1, Table 5.7-1)

Total Load = 15,905 + 2,700 = 18,605 LB < 32,500 Lb
<u>Acceptable</u>

6.3 <u>PCRV Concrete</u>

The PCRV concrete was designed to be in a net compressive state of stress during the life of the plant. Previously analyzed loading conditions include initial prestress at atmospheric pressure, before heating at atmospheric pressure, design temperature at reference pressure, design temperature at 1.15X reference pressure, start of operation at working pressure, end of operation at reference pressure, and end of operation at atmospheric pressure (Ref. 8.1, Section 5.3). This compressive stress is due to the tensioning of the tendons which envelope the PCRV.

The effects of the proposed System 46 temperature change upon the PCRV concrete will now be investigated. Both long term and short term effects will be considered.

First, consider the case in which the System 46 temperature change has been in effect for a period of time such that thermal equilibrium has been established. This would have the effect of reducing the net effective bulk temperature of the PCRV concrete. A bulk temperature decrease of the PCRV would have the effect of shrinking the PCRV and causing a decrease in the concrete compressive stress if the tendons were assumed to remain at the original higher temperature by some mechanism. A conservative measure of this decrease in compressive stress can be made as follows:

The strain in a segment of concrete subjected to a 15°F temperature drop is

$$Strain = \frac{Change\ in\ Length}{Original\ Length}$$

$$= \frac{\alpha\ \Delta T\ L}{L}$$

$$= \alpha \Delta T$$

$where\ \alpha = coefficient\ of\ thermal\ expansion$

$= 4.4 \times 10^{-6}\ In/In - {}^{\circ}F$ (Ref. 1, Section E.6.4)

$\Delta T = 15^{\circ}F$

$$Strain = (4.4 \times 10^{-6})(15) = 0.000066 \ll 0.003\ allowable\ per\ ACI\ 318\text{-}89$$
$$or\ 0.0066\%$$

The tendons were initially strained 0.61% (Ref. 8.1, Table 5.6-5). The change in the initial concrete compressive stress would then be on the order of the concrete strain divided by the initial tendon strain or

$$\frac{0.0066}{0.61} = 0.011\ or\ 1.1\%$$

This change was conservatively calculated and is considered to be negligible, particularly in view of the fact that the PCRV is pressurized to a very low level for the proposed case (5 PSI maximum, Ref. 8.1).

Now, consider effects which could occur shortly after the beginning of temperature change. During the initiation of the proposed temperature change it is possible that some tensile stresses would develop on the inner surface of the PCRV concrete due to a non-uniform temperature distribution. The limiting case for this stress would occur if the PCRV concrete adjacent to the System 46 cooling tubes was assumed to instantly cool off the 15°F proposed for the event. In this case the resulting maximum tensile stress at the concrete surface due to the restraint of the adjacent concrete would be:

$$\sigma = \frac{\Delta T\, \alpha\, E}{2\left(1-\mu\right) LN \frac{c}{b}} \left| 1 - \frac{2c^2}{c^2-b^2} LN \frac{c}{b} \right|$$

(Ref. 8.3, Pg. 377, Article 88, Case 16)

where

$\Delta T = 15°F\ Assumed$

$\alpha = 4.4 \times 10^{-6}\, In/In - °F$ (Ref. 8.1, Section E.10.3)

$E = 4.82 \times 10^{6}\, PSI$

$\mu = 0.1667$

$c = Outer\ Radius\ of\ PCRV = 186 + (9 \times 12) = 294"$

$b = Inner\ Radius\ of\ PCRV = 31' \times 12 \times 1/2 = 186"$

$$\sigma = \frac{\left(15\right)\left(4.4 \times 10^{-6}\right)\left(4.82 \times 10^{6}\right)}{\left(2\right)\left(1-0.1667\right) LN \frac{294}{186}} \left| 1 - \frac{\left(2\right)\left(294^2\right)}{\left(294^2 - 186^2\right)} LN \frac{294}{186} \right|$$

$\sigma = 220\, PSI < 233\, PSI$ (Ref. 8.1, Section 5.4.4.3)

The calculated worst case surface tensile stress is very conservative and is lower than the Ref. 8.1 allowable for unreinforced concrete. This stress would tend to partially relieve the compressive stress which exists in the depressurized PCRV. This stress is not critical due to the presence of bonded reinforcing steel.

6.4 PCRV Penetrations

The General Arrangement Drawings (Ref. 8.1, Figures 5.1-1 and 5.8-5) show the locations of the various penetrations through the walls and heads of the PCRV. All of the PCRV penetrations have carbon steel liners approximately 1/2 inch to 2 inch thick. The penetration liners are welded directly to the PCRV liner to maintain the continuity of the membrane enclosing the primary coolant (Ref. 8.1, Section 5.8.1).

All original primary closures are designed in accordance with the principles of ASME Boiler and Pressure Vessel Code, Section III, Class A, with a design pressure equal to the PCRV Reference Pressure of 845 psig. The combination of the various loads is in accordance with the rules of ASME Section III for Class A vessels for primary closures.

During the proposed reduction in System 46 operating temperatures the PCRV penetrations could possibly be subjected to an increase in stress levels. This stress could develop due to restraint of the penetration's thermal contraction due to the restraint offered by the adjacent concrete or by the penetration material itself. The limiting case for this differential thermal expansion induced stress can be calculated by assuming that the 15°F temperature change occurs instantly and that complete restraint is provided to any thermal movement. In this case, the maximum stress can be calculated as follows:

$$\sigma = \Delta T \, \alpha \, E / \left(1 - \mu \right) \qquad \text{(Ref. 8.3, Case 2, Pg. 374)}$$

where

$$\Delta T = 15°F \quad \textit{(Assumed, Worst Case)}$$

$$\alpha = \textit{Coefficient of Thermal Expansion}$$

$$= 6.5 \times 10^{-6} \; In/In - °F$$

$$E = \textit{modulus of elasticity} = 30 \times 10^{6} \, PSI$$

$$\mu = \textit{Poissons Ratio} = 0.3$$

The values of α, E, and μ above are typical values for carbon steel. The penetrations are made of various grades of carbon steel (Ref. 1, Section 5.8.2.1) which may have slightly different values. The total stress levels in the penetrations are insensitive to these small variations.

$$\sigma = \left(15\right)\left(6.5 \times 10^{-6}\right)\left(30 \times 10^{6}\right) / \left(1 - 0.3\right) = 4{,}179 \, PSI \quad \textit{(TENSION)}$$

The tensile stress of 4,179 PSI calculated above is very conservative and represents the worst case value. This value will be added to the typical penetration stress analysis results found in Table 5.8 3 of Ref. 8.1 in a conservative manner. As the calculated stress is self-limiting it is secondary in nature. It will be added to primary + secondary membrane + bending stresses of line 5 of Table 5.8.-3.

PENETRATION		STRESS INTENSITY (PSI)	STRESS LIMIT (PSI)
BOTTOM ACCESS PENETRATION	PRIMARY	36,355 + 4,179 = 40,534	69,300
	SECONDARY	37,139 + 4,179 = 41,318	52,500
HELIUM CIRCULATOR PENETRATION	PRIMARY	31,845 + 4,179 = 36,024	52,500
	SECONDARY	32,593 + 4,179 = 36,722	52,500
REFUELING PENETRATION	PRIMARY	15,240 + 4,179 = 19,419	52,500
	SECONDARY	29,900 + 4,179 = 34,079	52,500
TOP ACCESS PENETRATIONS	PRIMARY	37,700 + 4,179 = 41,879	69,300
	SECONDARY	2[illegible]410 + 4,179 = 30,589	52,500

It is seen from above that with the addition of the conservatively calculated thermal stresses that there is still a wide margin between the total stresses and the allowable stresses. It is anticipated that fewer than 10 cycles of the proposed temperature variation will occur. The fatigue damage due to even 10 times this amount (100 cycles) will be insignificant. It is concluded that the penetrations are structurally adequate for the proposed temperature variation.

6.5 PCRV Tendons

The PCRV tendons were tensioned after the concrete was placed and before the initial pressurization of the PCRV. The tensioning of the tendons serves to yield a net compressive stress in the PCRV concrete and liner during the entire life history of the plant.

The highest state of tensile stress in the tendons existed immediately after the initial prestressing. After this time the effects of concrete shrinkage and creep tend to decrease somewhat the tendon tension. (See Ref. 8.1, Table 5.3-2).

The proposed temperature change is enveloped by the PCRV analysis previously performed. The results of this analysis are reported in Ref. 8.1, Table 5.3-2. It is concluded that the PCRV tendons are acceptable for the proposed temperature change.

6.6 PCRV Reinforcing Rods

Bonded reinforcement is provided in the PCRV to resist the computed forces and to distribute concrete cracks (Ref. 8.1, Section 5.5.1). The rebar is generally in a state of compression due to prestress applied by the PCRV tendons. This state of compression exists at the reactor reference pressure (845 PSIG).

The proposed temperature change is enveloped by the PCRV analysis previously performed. The results of this analysis are reported in Ref. 8.1, Table 5.3-2. It is concluded that the PCRV reinforcing rods are acceptable for the proposed temperature change.

6.7 Core Support Floor Liner

The Core Support Floor (CSF) is an insulated and water cooled composite concrete and steel structure. The CSF is encased in a 3/4 inch thick steel liner (see Figure 6.1). The top and bottom surfaces of the liner have welded studs which are embedded in the CSF concrete and which enable the liner and concrete to act as a composite structure. The top, bottom, and sides of the liner have cooling tubes welded to them for which System 46 provides cooling water.

During the proposed System 46 operating temperature change it is possible that the liner would be subjected to an increase in stress level. This possible stress would be due to differential thermal expansion between the liner and the concrete due to the fact that the thin liner would respond more quickly than the concrete to System 46 temperature variations.

The limiting case for this thermal stress can be calculated by assuming that the liner instantly experiences the entire 15°F temperature drop of the proposed scenario and, further, that the thermal strains due to this temperature drop are totally restrained. In this case the thermal stress can be calculated as follows:

$$\sigma = \Delta T\, \alpha\, E/(1 - \mu) \qquad \text{(Ref. 8.3, Pg. 374, Article 88, Case 2)}$$

where

$$\Delta T = 15°F \textit{ (assumed)}$$

$$\alpha = 6.5 \times 10^{-6}\, In/In - °F \qquad \text{(Ref. 8.4, Pg. 4)}$$

$$E = 29 \times 10^{6}\, PSI$$

$$\mu = 0.3$$

$$\sigma = \left(15\right)\left(6.5 \times 10^{-6}\right)\left(29 \times 10^{6}\right)/\left(1 - 0.3\right)$$

$$= 4{,}039\, PSI$$

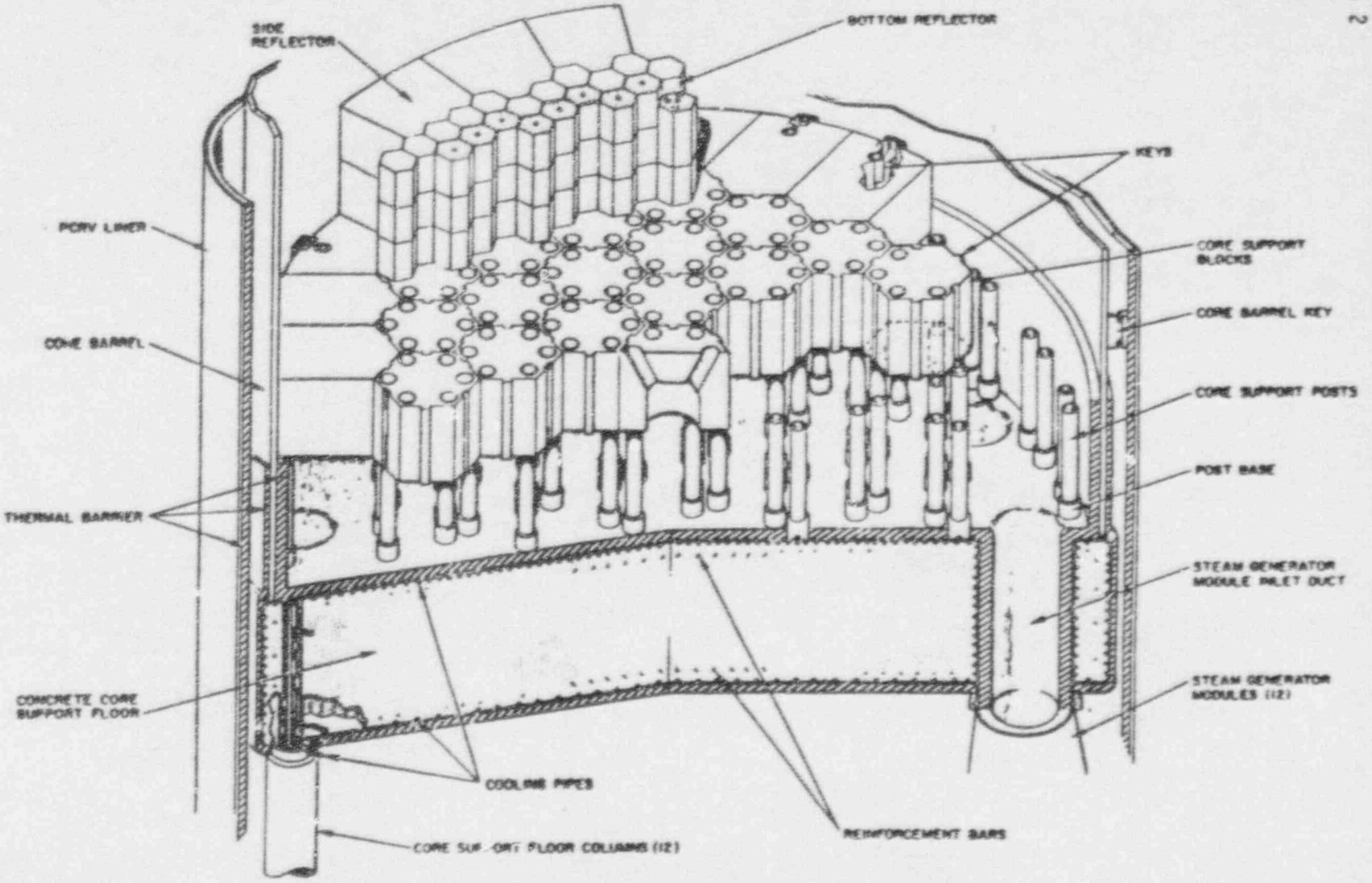


Figure 6.1 Core Support Arrangement

Add this thermal stress to previously calculated stresses (from Ref. 8.1, Table 3.3-3) and compare to the allowable.

Area	Stress (PSI)	Allowable (PSI)
Liner - maximum tensile stress	2,600 + 4,039 = 6,639	23,100
Liner - support column junction	58,500 + 4,039 = 62,539	69,300

The CSF liner stresses are acceptable with the addition of the conservatively calculated thermal stress. It is anticipated that fewer than 10 cycles of the proposed temperature variation will occur. The fatigue damage due to even 10 times this amount (100 cycles) will be insignificant. It is concluded that the CSF liner is structurally adequate for the proposed System 46 operating temperature range.

6.8 Core Support Floor Concrete

The CSF concrete would possibly be subjected to some thermally induced stresses due to the initiation of the proposed temperature change. This stress would arise due to a non-uniform temperature distribution in the CSF concrete resulting from the fact that the surface of the concrete adjacent to the cooling tubes would respond more quickly to System 46 temperature variations than the concrete some distance from the surface concrete due to a non-uniform temperature distribution. The limiting case for this stress would occur if the PCRV concrete adjacent to the System 46 cooling tubes was assumed to instantly cool off the 15°F proposed for the event. In this case the resulting maximum tensile stress at the concrete surface due to the restraint of the adjacent concrete would be:

$$\sigma = \Delta T \, \alpha \, E \, / \left(1 - \mu\right)$$ (Ref. 8.3, Pg. 375, Article 88, Case 9)

where

$\Delta T = 15°F \; Assumed$

$\alpha = 4.4 \times 10^{-6} \; In/In - °F$

$E = 4.82 \times 10^{6} \, PSI$

$\mu = 0.1667$

(Ref. 8.1, Section E.10.3)

$$\sigma = \left(15\right)\left(4.4 \times 10^{-6}\right)\left(4.82 \times 10^{6}\right) / \left(1 - 0.1667\right) = 382 \, PSI$$

This stress is somewhat higher than the allowable tensile stress of 232 PSI for unreinforced concrete (Ref. 8.1, Section 5.4.4.3) but is of no consequence due to the presence of bonded reinforcing steel.

6.9 Core Support Floor Reinforcing Bars

The reinforcing bars of the CSF are subject to low levels of stress. The calculated rebar stress including the effect of the liner is 2300 PSI which is an order of magnitude lower than the 24,000 PSI allowable stress (Ref. 8.1, Table 3.3-3).

The rebar is in intimate contact with the CSF concrete with the result that the rebar and concrete will change temperature at the same rate. The temperatures anticipated for the proposed scenario are well within the bounds of ordinary reinforced concrete and no deleterious effects upon the rebar are anticipated. It is concluded that the CSF reinforcing rods are adequate for the proposed System 46 operating temperature change.

6.10 Fracture Mechanics Evaluation of the PCRV Liner Materials

FSAR Sections 5.7.2.2 and E.24.5 discuss the experimentally determined initial and final NIL Ductility Transition (NDT) temperatures following exposure of each heat of liner material and a weldment of the liner material to an integrated neutron dose of 2.3 E18 n/cm^2 (E ≧ 1 MeV). This integrated neutron dose utilized in the materials testing was the dose calculated for the most highly irradiated portion of the liner, at the top head, assuming a 30 year operational life at an 80% capacity factor (24 effective full power years, or 8760 effective full power days - EFPD). Each of the four heats of liner material had an initial NDT temperature below minus 60°F and experienced an increase in NDT temperature of less than 100°F (FSAR Table E.24-16) following exposure to the 2.3 E18 n/cm^2 integrated neutron flux. The weld metal had an initial NDT temperature of minus 75°F and experienced an increase in NDT temperature of 125°F (FSAR Table E.24-16) following exposure to this same integrated neutron flux.

The reactor was permanently shut down on August 18, 1989, having accumulated 890 EFPD, which represents approximately one-tenth of the design lifetime and which corresponds to a maximum integrated neutron dose at the top head liner of 2.4 E17 n/cm^2 (based on the integrated neutron flux equation in FSAR Section 5.7.2.2). Assuming a linear correlation between neutron exposure and increase in the NDT temperatures, this neutron exposure would cause a shift in the NDT temperatures of approximately one-tenth (890/8760) of the experimentally determined NDT temperature shifts. The NDT temperatures are calculated to shift from minus 60°F to minus 50°F for the liner material and from minus 75°F to minus 62°F for the weldment material over the actual operating life of the reactor. The Fracture Transition Elastic (FTE) temperature is approximately equal to the NDT + 60°F. The end-of-life FTE temperatures are therefore calculated to be 10°F for the liner material and minus 2°F for the weldment material.

Maintaining the liner temperature above these FTE temperatures ensures that crack propagation in the liner at any tensile membrane stress up to yield stress would be incredible, and in this respect the liner meets the same criteria as are prescribed for steel nuclear pressure vessels, but is more conservative since the liner is in general compression during shutdown conditions, as it also was for all normal operating modes. Since the new 85°F minimum operating temperature of the PCRV liner is above the calculated end-of-life FTE temperatures of the liner and weldment materials, it is acceptable.

7.0 CONCLUSIONS

The PCRV and CSF areas judged to be the most critical were analyzed for the conditions induced by the proposed 15°F System 46 temperature change. These areas were the PCRV liner, the PCRV liner anchor studs, the PCRV concrete, the PCRV penetration, the PCRV tendons, the PCRV reinforcing rods, the CSF liner, the CSF concrete, and the CSF reinforcing rods. The stresses due to the proposed 15°F were added in a conservative manner to stresses due to other loading conditions and were found to be within the allowable stresses as summarized in Section 2.0 of this EE.

It is concluded that the PCRV and CSF structures are structurally adequate for stresses due to the decrease of the average of the inlet and outlet temperatures from the 100°F specified in LCO 4.2.15 (e) to 85°F. This conclusion is based upon the premise that the maximum water outlet temperature is lowered from 120°F to 105°F (LCO 4.2.15 condition "b") and that no changes are made to conditions a, c, or d of LCO 4.2.15 (see Section 4.0 of this EE).

It is concluded that an adequate margin exists between the Nil Ductility Transition temperatures of the PCRV liner materials and the proposed 85°F temperature and that the liner materials will remain ductile at this temperature.

It is further concluded that adequate margins exist in the stresses and above the NDT temperature to allow an additional decrease in the average of the inlet and outlet temperatures should this become desirable. Any additional temperature decrease would require further analysis.

8.0 REFERENCES

8.1 Fort St. Vrain Nuclear Generating Station, Updated Final Safety Analysis Report, Revision 9.

8.2 Technical Specification LCO 4.7.1.

8.3 Formulas for Stress and Strain, 4th Edition, Raymond J. Roark.

8.4 Stress Analysis for PSC/PCRV, GADR-12 (Vol. 1), dated 4/23/71.

8.5 Mechanics of Materials, 2nd Edition, Higdow

Public Service

FORT ST. VRAIN NUCLEAR GENERATING STATION

PUBLIC SERVICE COMPANY OF COLORADO

CHECK LIST OF DESIGN VERIFICATION QUESTIONS FOR DESIGN REVIEW METHOD

EE-96-0007

CN REV. B

BY AKK 9.1

PAGE 1/1

YES	NO	N/A		
☑	☐	☐	1.	Were appropriate design inputs selected and incorporated into the design?
☑	☐	☐	2.	Are all assumptions used to perform the design activity adequately identified, described, reasonable?
☐	☐	☑	3.	Have appropriate quality assurance requirements been specified?
☑	☐	☐	4.	Has documentation to assure the quality of design been provided or reference made in Design Background Information Package?
☑	☐	☐	5.	Are the codes, standards, and regulatory requirements, including issue and adder incorporated into the Design Background Information Package?
☑	☐	☐	6.	Have applicable construction, operating, and design experience been considered, such as fail trends or equipment operating history (NPRDS)?
☐	☐	☑	7.	Have the design interface considerations been addressed and satisfied?
☑	☐	☐	8.	Was an appropriate design method used?
☑	☐	☐	9.	Are the design outputs reasonable compared to the design inputs?
☐	☐	☑	10.	Are the specified parts, equipment, and processes suitable for the required application?
☐	☐	☑	11.	Are the specified materials compatible with each other and the design environmental and proc conditions to which the material will be exposed?
☐	☐	☑	12.	Have maintenance features or requirements which need to be addressed been included in Design Background Information Package and/or the Procurement, Installation and T Requirements Package?
☐	☐	☑	13.	Have accessibility and other design provisions been provided to allow future maintenan repairs, and in-service inspections to be performed?
☑	☐	☐	14.	Has the design properly considered and addressed radiation exposure to the public and plant personnel?
☑	☐	☐	15.	Are the acceptance criteria incorporated in the modification package sufficient to all verification that design input requirements have been satisfactorily accomplished?
☐	☐	☑	16.	Have adequate pre-operational and/or subsequent periodic test requirements been specified?
☐	☐	☑	17.	Are adequate handling, storage, and cleanliness requirements specified?
☐	☐	☑	18.	Are adequate identification requirements specified?
☐	☐	☑	19.	Has adequate documentation been included in the CN package to allow/provide the preparat of CWP(s) and the construction of the modification?
☐	☐	☑	20.	Have adequate document mark-up(s) been included to allow the update and maintenance design documents?

NOTE: If the answer to any question is no, provide additional information and resolution below.

RESOLUTION OF DESIGN DEFICIENCIES UNCOVERED DURING THE DESIGN VERIFICATION PROCESS