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LMFBR Demonstration Plant
Steam Generator

MASTER

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CONCEPT AND PRELIMINARY DESIGN OF DOUBLE
TUBESHEET CONNECTOR REGION FOR DESIGN AND
STEADY-STATE CONDITIONS

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1.0 Introduction

In this analysis the structural integrity of the double tubesheet connector for the LMFBR demonstration plant steam generator is investigated for design and steady state conditions. Although the evaporator and superheater are to be interchangeable, only the steam outlet end of the evaporator is investigated here. This was selected because the mean temperature differences between the tubesheets, tubes and connector are largest here at steady state, thus yielding the highest thermal loads. Combined with the thermal loads are superheater pressures in order to also use the highest mechanical loads. Although this is a conservative approach for the evaporator, the superheater must be analyzed separately at a later date in order to assure interchangeability. Evaluation of the results is based upon ASME Code Case 1331-8 [1]. The design and steady state conditions are each investigated for two cases. First it is assumed that the tubes are bonded, i.e., the inner tube is fixed at the bottom of the steam tubesheet and the outer tube is fixed at the bottom of the sodium tubesheet. Second, it is assumed that the tubes are free, i.e., the inner tube is fixed at the bottom of the steam tubesheet and the outer tube is fixed to the inner tube where the U-bend region begins. A major difficulty in the analysis is assuring the integrity of the connector under the wide range of load conditions encountered by considering the tubes both fixed and free and at the same time minimizing the interaction forces on the tubes.

2.0 Geometry/Model Description

The geometry of the double tubesheet connector is shown in Figures 1 and 2. The material for the steam generator components is 2½ Cr-1Mo. The material properties used are given in the attachment.

The mathematical model is shown in Figure 3. The model is represented by 100 shell elements which permit the applied loads and deflections as shown. The computer program used is Seal Shell IV [2]. An interaction analysis is first performed to determine the appropriate applied forces.

It should be noted that in the shell model, the additional thickness at the junctions to the tubesheets is added on each side of the midsurface. During manufacture this additional material will all be on the inside surface for forging purposes. No resultant change in flexibility is expected, however, some redistribution of load from outside to inside is anticipated.

It should also be noted that tubesheet rotations and axial growth of the tubes due to poisson's effect from internal pressure have been neglected.

3.0 Double Tubesheet Connector and Tube Flexibilities

The axial flexibility of the connector region was determined by making a preliminary computer run with an applied axial force F_{zn} and all other boundary conditions with zero displacement or rotations. Hence, the axial flexibility is given by:

$$f_r = \frac{\delta_{zn}}{F_{zn}} \quad (1)$$

Note that total loads are used and not loads per unit of circumference. For the case when the tubes are fixed (Figure 4) the flexibilities are determined by the following.

$$f_t = \frac{L}{NAE} \quad (2)$$

L = length of tube

N = numbers of tubes

A = cross-sectional area of tube

E = modulus of elasticity

For the free case (Figure 5) an analysis^[3] was performed to determine the flexibility of an inner and outer tube system. The results indicate that for $E=26.8 \times 10^6$ psi:

$$f = 3.0238 \times 10^{-4} \text{ in/lb} \quad (3)$$

In order to utilize this flexibility in the interaction analysis it must be separated into the inner and outer tube flexibilities. The total flexibility is first divided by the number of tubes (N) and adjusted to the appropriate value of E_t (assumed to be the value at the average temperature of the inner and outer tube).

$$f_t = \frac{f}{N} \frac{E}{E_t} \quad (4)$$

The inner and outer tube flexibilities are then determined by the ratio of tube cross-sectional areas.

$$f_{to} = f_t \left(\frac{A_i}{A_o + A_i} \right) \quad (5)$$

$$f_{ti} = \left(\frac{A_o}{A_o + A_i} \right) \quad (6)$$

4.0 Interaction Forces and Compatibility

To determine the interaction force, equilibrium and compatibility must be assured. The interaction force is separated into axial force due to pressure and axial force due to thermal loads such that load controlled and deformation controlled stresses can be obtained.

4.1 Tubes Fixed

Referencing Figure 4 for the case when the tubes are fixed the following is obtained.

Pressure loads

$$\text{Equilibrium} \quad \Sigma F=0 \quad X_t + X_r - P = 0$$

$$\text{Compatibility} \quad X_t f_t + X_t * f_{t*} = X_r f_r$$

The tubesheet is assumed to be rigid, hence it does not appear in the equations. Solving the above yields the pressure forces.

$$X_t = \frac{P f_r}{f_t + f_{t*} + f_r} \quad (7)$$

$$X_r = P - X_t \quad (8)$$

For this case P is defined by:

$$P = P_i (A_{ts} - A_{to}) + P_{H_2O} (A_{ti}) \quad (9)$$

P_i = helium pressure

A_{ts} = area of sodium tubesheet

A_{to} = outside area of outer tube

P_{H_2O} = steam pressure

A_{ti} = inside area of inner tube

Note that the pressure acting on the cross-sectional area of the outer tube is neglected.

Thermal Loads

$$\text{Equilibrium} \quad \Sigma F=0 \quad X_t + X_r = 0$$

$$\text{Compatibility} \quad X_t(f_t + f_{t*}) + \delta_t + \delta_{t*} = X_r f_r + \delta_r + \delta_{ts}$$

Solving the above equations simultaneously yields the following thermal forces.

$$X_t = \frac{\delta_r + \delta_{ts} - \delta_t - \delta_{t*}}{f_t + f_{t*} + f_r} \quad (10)$$

$$X_r = -X_t \quad (11)$$

The deflections above are defined as follows.

δ_r = deflection of reducer determined from Seal Shell computer run

δ_{ts} = $\alpha \Delta T$ deflection of tubesheet

δ_t = $\alpha \Delta T$ deflection of inner tube

δ_{t*} = $\alpha \Delta T$ deflection of inner and outer tube inside sodium tubesheet

4.2 Tubes Free

Interaction forces for the free case are determined in a similar manner (Reference Figure 5).

Pressure Loads

$$\text{Equilibrium} \quad \Sigma F=0 \quad X_r + X_{ti} - P = 0$$

$$X_{to} + X_{ti} - P + F = 0$$

$$\text{Compatibility} \quad X_{ti} f_{ti} = X_r f_r + X_{to} f_{to}$$

Solving the above simultaneously yields the pressure loads.

$$X_{ti} = \frac{P f_r + (P - F) f_{to}}{f_{ti} + f_r + f_{to}} \quad (12)$$

$$X_r = P - X_{ti} \quad (13)$$

$$X_{to} = P - F - X_{ti} \quad (14)$$

For this case P is defined by equation 9 and F is defined by the first component of the equation.

$$F = P_i (A_{ts} - A_{to})$$

Thermal Loads

$$\text{Equilibrium } \Sigma F=0 \quad X_r = X_{to}$$

$$X_r + X_{ti} = 0$$

$$\text{Compatibility} \quad X_r(f_r + f_{to}) + \delta_r + \delta_{ts} + \delta_{to} = X_{ti}f_{ti} + \delta_{ti}$$

Solving the above yields the thermal forces for the free case.

$$X_r = \frac{\delta_{ti} - \delta_r - \delta_{ts} - \delta_{to}}{f_r + f_{to} + f_{ti}} \quad (15)$$

$$X_{to} = X_r \quad (16)$$

$$X_{ti} = -X_r \quad (17)$$

The deflections above are defined similarly to the fixed case.

5.0 Design Conditions

5.1 Tubes Fixed

Interaction and Boundary Conditions for the design conditions with the tubes fixed the pressure loads are given as follows (equ. (7) and (8), figure 4.)

$$X_t = \frac{P f_r}{f_t + f_{t*} + f_r}$$

$$X_r = P - X_t$$

$$\text{where } P = P_i (A_{ts} - A_{to}) + P_{H_2O} (A_{ti})$$

$$P_i = 300 \text{ psi}$$

$$A_{ts} = \pi R_i^2 = 3.14(45.5^2) = 6501 \text{ in}^2$$

$$A_{to} = \frac{\pi D_o^2}{4} \times N = \frac{3.14(.875^2)(715)}{4} = 430 \text{ in}^2$$

$$P_{H_2O} = 1785 \text{ psi}$$

$$A_{ti} = \pi R_i^2 N = 3.14(.2715^2)(715) = 165 \text{ in}^2$$

$$P = 300(6501 - 430) + 1785(165)$$

$$P = 1821300 + 294525$$

$$P = 2115825 \text{ lbs.}$$

$$f_r = 4.126 \times 10^{-8} \text{ in/lb} \quad \text{Computer Job \#1714}$$

$$f_t = \frac{\ell}{NAE} \quad \begin{aligned} A_i &= .1699 \text{ in}^2 \\ A_o &= .1997 \text{ in}^2 \end{aligned}$$

$$\ell = 20 \text{ in.}$$

$$N = 715$$

$$A = .1699 \text{ in}^2$$

$$E = \text{at design steam temperature } 650^\circ\text{F} = 27 \times 10^6 \text{ psi}$$

$$f_t = \frac{20 \times 10^{-6}}{715(.1699)(27)} = .609 \times 10^{-8} \text{ in/lb}$$

$$f_{t*} = \frac{l}{NAE}$$

$$l = 12 \text{ in.}$$

$$N = 715$$

$$A = .1699 + .1997 = .3696 \text{ in}^2$$

$$E = \text{at design steam temperature } 650^\circ\text{F} = 27 \times 10^6 \text{ psi}$$

$$f_{t*} = \frac{12 \times 10^{-6}}{715(.3696)(27)} = .168 \times 10^{-8} \text{ in/lb}$$

$$X_t = \frac{2115825(4.126)}{.609 + .168 + 4.126} = 1780521 \text{ lbs.}$$

$$X_r = 2115825 - 1780521 = 335304 \text{ lbs.}$$

The thermal loads are given by equations (10) and (11).

$$X_t = \frac{\delta_r + \delta_{ts} - \delta_t - \delta_{t*}}{f_t + f_{t*} + f_r}$$

$$X_r = -X_t$$

$$\delta_r = 0.16 \text{ in.} \quad \text{Computer Job \#1231}$$

$$\delta_{ts} = l\alpha\Delta T$$

$$l = 12 \text{ in.}$$

$$\Delta T = 890^\circ\text{F design temperature of sodium tubesheet}$$

$$\alpha = 7.7 \times 10^{-6} \text{ in/in-}^\circ\text{F}$$

$$\delta_{ts} = 12(7.7)(10^{-6})(890) = .082 \text{ in.}$$

$$\delta_t = l\alpha\Delta T$$

$$l = 20 \text{ in.}$$

$$\Delta T = 650^\circ\text{F design temperature of steam outlet}$$

$$\alpha = 7.44 \times 10^{-6} \text{ in/in-}^\circ\text{F}$$

$$\delta_t = 20(7.44)(10^{-6})(650) = .097 \text{ in.}$$

$$\delta_{t*} = l\alpha\Delta T$$

$$l = 12 \text{ in.}$$

$$\Delta T = 650^\circ\text{F design temperature of steam outlet}$$

$$\alpha = 7.44 \times 10^{-6} \text{ in/in-}^\circ\text{F}$$

$$\delta_{t*} = 12(7.44)(10^{-6})(650) = .058 \text{ in.}$$

$$X_t = \frac{(.016 + .082 - .097 - .058)}{.609 + .168 + 4.126} = -1162553 \text{ lbs.}$$

$$X_r = 1162553 \text{ lbs.}$$

The total loads pressure plus thermal are:

$$X_t = 1780521 - 1162553 = 617968 \text{ lbs.}$$

$$X_r = 335304 + 1162553 = 1497857 \text{ lbs.}$$

Two computer runs were made for each case examined in order to separate out the primary bendings stresses. The applied boundary conditions (reference Figure 3) for the case of design conditions with the tubes fixed are shown in Table 1.

5.2 Tubes Free

For design conditions with the tubes free equations (12), (13), and (14) give the pressure loads (Figure 5).

$$X_{ti} = \frac{Pf_r + (P-F)F_{to}}{f_{ti} + f_r + f_{to}}$$

$$X_r = P - X_{ti}$$

$$X_{to} = P - F - X_{ti}$$

For this case:

$$P = 2115825 \text{ lbs.}$$

$$F = 1821300 \text{ lbs.}$$

$$f_r = 4.126 \times 10^{-8} \text{ in/lb}$$

To calculate f_{ti} and f_{to} equations (4), (5), and (6) are used.

$$f_t = \frac{F E}{N E_t}$$

$$f = 3.0238 \times 10^{-4} \text{ in/lb}$$

$$N = 715$$

$$E = 26.8 \times 10^6 \text{ psi}$$

E_t at the average temperature of the inner and outer tube
 $(765+850)/2 = 808^\circ\text{F}$

$$E_t = 25.5 \times 10^6 \text{ psi}$$

$$f_t = \frac{3.0236(26.8)(10^2)}{715(25.5)(10^6)} = 44.447 \times 10^{-8} \text{ in/lb}$$

$$f_{to} = f_t \left(\frac{A_i}{A_i + A_o} \right) \quad f_{ti} = f_t \left(\frac{A_o}{A_i + A_o} \right)$$

$$A_i = .1699 \text{ in}^2$$

$$A_o = .1977 \text{ in}^2$$

$$f_{to} = 44.447(10^{-8}) \left(\frac{.1699}{.1699+.1997} \right) = 20.401 \text{ in/lb}$$

$$f_{ti} = 44.447(10^{-8}) \left(\frac{.1997}{.1699+.1997} \right) = 24.046 \text{ in/lb}$$

$$X_{ti} = \frac{(2115825)(4.126) + (2115825 - 1821300)(20.401)}{24.046 + 4.126 + 20.401}$$

$$X_{ti} = 303430 \text{ lbs.}$$

$$X_r = 2115825 - 303430 = 1812395 \text{ lbs.}$$

$$X_{to} = 2115825 - 1821300 - 303430 = -8905 \text{ lbs.}$$

The thermal loads for the free case are given by equations (15), (16), and (17).

$$X_r = \frac{\delta_{ti} - \delta_r - \delta_{ts} - \delta_{to}}{f_r + f_{to} + f_{ti}}$$

$$X_{to} = X_r$$

$$X_{ti} = -X_r$$

$$\delta_{ti} = \ell_1 \alpha \Delta T + \ell_2 \alpha_2 \Delta T_2$$

$$\ell_1 = 32 \text{ in.}$$

$$\ell_2 = 487 \text{ in.}$$

$$\Delta T_1 = 650^\circ\text{F design temperature of steam tubesheet}$$

$\Delta T_2 = 765^\circ\text{F}$ design temperature of inner tube

$$\alpha_1 = 7.44 \times 10^{-6} \text{ in/in-}^\circ\text{F}$$

$$\alpha_2 = 7.60 \times 10^{-6} \text{ in/in-}^\circ\text{F}$$

$$\delta_{ti} = 32(7.44)(10^{-6})(650) + 487(7.60)(10^{-6})(765)$$

$$\delta_{ti} = 2.986 \text{ in.}$$

$$\delta_r = .016 \text{ in.} \quad \text{Computer Job \#1684}$$

$$\delta_{ts} = l\alpha\Delta T$$

$$l = 12 \text{ in.}$$

$\Delta T = 890^\circ\text{F}$ design temperature of sodium tubesheet

$$\alpha = 7.7 \times 10^{-6} \text{ in/in-}^\circ\text{F}$$

$$\delta_{ts} = 12(7.7)(10^{-6})(890) = .082 \text{ in.}$$

$$\delta_{to} = l\alpha\Delta T$$

$$l = 487$$

$\Delta T = 850^\circ\text{F}$ design temperature of outer tube

$$\alpha = 7.7 \times 10^{-6} \text{ in/in-}^\circ\text{F}$$

$$\delta_{to} = 487(7.7)(10^{-6})(850) = 3.187 \text{ in.}$$

$$X_r = \frac{(2.986 - .016 - .082 - 3.187)10^8}{4.126 + 20.401 + 24.046} = -615568 \text{ lbs.}$$

$$X_{to} = -615568 \text{ lbs.}$$

$$X_{ti} = 615568 \text{ lbs.}$$

The total loads pressure plus thermal are:

$$X_{ti} = 303430 + 615568 = 918998 \text{ lbs.}$$

$$X_{to} = -8905 - 615568 = -624473 \text{ lbs.}$$

$$X_r = 1812395 - 615568 = 1196827 \text{ lbs.}$$

The applied boundary conditions for design conditions with the tubes free are shown in Table 2.

6.0 Steady State Conditions

6.1 Tubes Fixed

For operating conditions with the tubes fixed, equations (7) and (8) yield the pressure loads.

$$X_t = \frac{Pf_r}{f_t + f_{t*} + f_r}$$

$$X_r = P - X_t$$

where $P = P_i (A_{ts} - A_{to}) + P_{H_2O} (A_{ti})$

$$P_i =$$

$$A_{ts} = 6501 \text{ in}^2$$

$$A_{to} = 430 \text{ in}^2$$

$$P_{H_2O} = 1660 \text{ psi}$$

$$A_{ti} = 165 \text{ in}^2$$

$$P = 260(6501 - 430) + 1660(165)$$

$$P = 1578460 + 273900$$

$$P = 1852360 \text{ lbs.}$$

$$f_r = 4.063 \times 10^{-8} \text{ in/lb} \quad \text{Computer Job \#1715}$$

$$f_t = \frac{l}{NAE} \quad \begin{aligned} A_i &= .1699 \text{ in}^2 \\ A_o &= .1997 \text{ in}^2 \end{aligned}$$

$$l = 20 \text{ in.}$$

$$N = 715$$

$$A = .1699 \text{ in}^2$$

$$E = \text{at steady state steam outlet temperature of } 610^\circ\text{F} \\ (\text{Figure 6}) = 27.4 \times 10^6 \text{ psi}$$

$$f_t = \frac{20 \times 10^{-6}}{715(.1699)(27.4)} = .601 \times 10^{-8} \text{ in/lb}$$

$$f_{t*} = \frac{l}{NAE}$$

$$l = 12 \text{ in.}$$

$$N = 715$$

$$A = .1699 + .1997 = .3696 \text{ in}^2$$

$$E = \text{at steady state steam outlet temperature of } 610^\circ\text{F} \\ (\text{Figure 6}) = 27.4 \times 10^6 \text{ psi}$$

$$f_{t*} = \frac{12 \times 10^{-6}}{715(.3696)27.4} = .165 \times 10^{-8} \text{ in/lb}$$

$$X_t = \frac{1852360(4.063)}{.601 + .165 + 4.063} = 1558529 \text{ lbs.}$$

$$X_r = 1852360 - 1558529 = 293831 \text{ lbs.}$$

The thermal loads are given by equations (10) and (11).

$$X_t = \frac{\delta_r + \delta_{ts} - \delta_t - \delta_{t*}}{f_t + f_{t*} + f_{tr}}$$

$$X_r = -X_t$$

$$\delta_r = .016 \text{ in.} \quad \text{Computer Job \#1258}$$

$$\delta_{ts} = l\alpha\Delta T$$

$$l = 12 \text{ in.}$$

$$\Delta T = 858^\circ\text{F steady state temperature of sodium tubesheet (Figure 6)}$$

$$\alpha = 7.69 \times 10^{-6} \text{ in/in-}^\circ\text{F}$$

$$\delta_{ts} = 12(7.69)(10^{-6})(858) = .079 \text{ in.}$$

$$\delta_t = l\alpha\Delta T$$

$$l = 20 \text{ in.}$$

$$\Delta T = 610^\circ\text{F steady state temperature of steam outlet (Figure 6)}$$

$$\alpha = 7.4 \times 10^{-6} \text{ in/in-}^\circ\text{F}$$

$$\delta_t = 20(7.4)(10^{-6})(610) = .090 \text{ in.}$$

$$\delta_t = l\alpha\Delta T$$

$$l = 12 \text{ in.}$$

$$\Delta T = 610^\circ\text{F steady state temperature of steam outlet (Figure 6)}$$

$$\alpha = 7.4 \times 10^{-6} \text{ in/in-}^\circ\text{F}$$

$$\delta_{t*} = 12(7.4)(10^{-6})(610) = .054 \text{ in.}$$

$$X_t = \frac{(.016 + .079 - .090 - .054)10^8}{.601 + .165 + 4.063} = -1014703 \text{ lbs.}$$

$$X_r = 1014703 \text{ lbs.}$$

The total loads pressure plus thermal are

$$X_t = 1558529 - 1014703 = 543826 \text{ lbs.}$$

$$X_r = 293831 + 1014703 = 1305534 \text{ lbs.}$$

The applied boundary conditions (reference figure 3) for the case of steady state conditions with the tubes fixed are shown in Table 3.

6.2 Tubes Free

For steady state conditions with the tubes free equations (12), (13), and (14) give the pressure loads (Figure 5).

$$X_{ti} = \frac{Pf_r + (P-F)f_{to}}{f_{ti} + f_r + f_{to}}$$

$$X_r = P - X_{ti}$$

$$X_{to} = P - F - X_{ti}$$

For this case

$$P = 1852360 \text{ lbs.}$$

$$F = 1578460 \text{ lbs.}$$

$$f_r = 4.063 \times 10^{-8} \text{ in/lb}$$

To calculate f_{ti} and f_{to} equations (4), (4), and (6) are used.

$$f_t = \frac{fE}{NE_o}$$

$$f = 3.0238 \times 10^{-4} \text{ in/lb}$$

$$N = 715$$

$$E = 26.8 \times 10^6 \text{ psi}$$

$$E_t \text{ at the average temperature of the inner and outer tube} \\ (665+715)/2 = 690^\circ\text{F}$$

$$E_t = 26.7 \times 10^6 \text{ psi}$$

$$f_t = \frac{3.0236(26.8)(10^2)}{715(26.7)(106)} = 42.449 \times 10^{-8} \text{ in/lb}$$

$$f_{to} = f_t \left(\frac{A_i}{A_i + A_o} \right) \quad f_{ti} = f_t \left(\frac{A_o}{A_i + A_o} \right)$$

$$A_i = .1699 \text{ in}^2$$

$$A_o = .1997 \text{ in}^2$$

$$f_{to} = 42.449(10^{-8}) \left(\frac{.1699}{.1699 + .1997} \right) = 19.484 \text{ in/lb}$$

$$f_{ti} = 42.449(10^{-8}) \left(\frac{.1997}{.1699 + .1997} \right) = 22.965$$

$$X_{ti} = \frac{(1852360)(4.063) + (1852360 - 1578460)19.484}{22.965 + 4.062 + 19.484}$$

$$X_{ti} = 276548 \text{ lbs.}$$

$$X_r = 1852360 - 276548 = 1575812 \text{ lbs.}$$

$$X_{to} = -2648 \text{ lbs.}$$

The thermal loads for the free case are given by equations (15), (16) and (17).

$$X_r = \frac{\delta_{Li} - \delta_r - \delta_{ts} - \delta_{to}}{f_r + f_{to} + f_{ti}}$$

$$X_{to} = X_r$$

$$X_{ti} = -X_r$$

$$\delta_{ti} = l_1 \alpha_1 \Delta T_1 + l_2 \alpha_2 \Delta T_2$$

$$l_1 = 32 \text{ in.}$$

$$l_2 = 487 \text{ in.}$$

$$\Delta T_1 = 610^\circ\text{F steady state steam outlet temperature (Figure 6)}$$

$$\Delta T_2 = 665^\circ\text{F steady state mean inner tube temperature (Figure 6)}$$

$$\alpha_1 = 7.4 \times 10^{-6} \text{ in/in-}^\circ\text{F}$$

$$\alpha_2 = 7.74 \times 10^{-6} \text{ in/in-}^\circ\text{F}$$

$$\delta_{ti} = 32(7.4)(10^{-6})(610) + 487(7.47)(10^{-6})(665)$$

$$\delta_{ti} = 2.564 \text{ in.}$$

$$\delta_r = .016 \text{ in.} \quad \text{Computer Job \#1272}$$

$$\delta_{ts} = l\alpha\Delta T$$

$$l = 12 \text{ in.}$$

$$\Delta T = 858^\circ\text{F steady state temperature of sodium tubesheet (Figure 6)}$$

$$\alpha = 7.69 \times 10^{-6} \text{ in/in-}^\circ\text{F}$$

$$\delta_{ts} = 12(7.69)(10^{-6})(858) = .079 \text{ in.}$$

$$\delta_{to} = l\alpha\Delta T$$

$$l = 487 \text{ in.}$$

$$\Delta T = 725^\circ\text{F steady state mean outer tube temperature (Figure 6)}$$

$$\alpha = 7.53 \times 10^{-6} \text{ in/in-}^\circ\text{F}$$

$$\delta_{to} = 487(7.53)(10^{-6})(725) = 2.659 \text{ in.}$$

$$X_r = \frac{(2.564 - .016 - .079 - 2.659)10^8}{4.063 + 19.484 + 22.965} = -408496$$

$$X_{ti} = 408496$$

$$X_{to} = -408496$$

The total loads pressure plus thermal are:

$$X_{ti} = 276548 + 408496 = 685044 \text{ lbs.}$$

$$X_{to} = -2648 - 408496 = -411144 \text{ lbs.}$$

$$X_r = 1575812 - 408496 = 1167316 \text{ lbs.}$$

The applied boundary conditions for steady state conditions with the tubes free are shown in Table 4.

7.0 Calculated Stresses and Evaluation of Results

The stresses which are calculated are those required for evaluation of the structure under design and normal conditions in accordance with ASME Code Case 1331-8. The particular locations of the structure investigated are shown in Figure 3. Also shown is the maximum temperature occurring at each location for design and steady-state. For the various stress categories the temperature dependent stress limits are selected at the maximum temperature occurring at the location and the time dependent stress limits are based on the unit operating at steady-state for its entire life, 2.63×10^5 hours.

For design conditions, the following stress limits must be satisfied.

$$P_m \leq S_o$$

$$(P_1 + P_b) \leq 1.5 S_o$$

For steady state conditions, the following stress limits must be satisfied.

$$P_m < S_{mt}$$

$$(P_1 + P_b) < \begin{cases} 1.5 S_m \\ K S_t \end{cases} \quad \text{smaller of}$$

$$\left[\left(P_1 + \frac{P_b}{K} + \right) Q_{\text{range}} \right] \leq S_q$$

The above equations are all defined in ASME Code Case 1331-8 [1].

The calculated stresses and code allowables for each condition investigated are given by

Condition	Table Number
Design-tubes fixed	5
Design-tubes free	6
Steady-state tubes fixed	7-8
Steady-state tubes free	9-10

Since the allowable stress intensities for any given condition are different due to differences in maximum temperature throughout the structure, the maximum stresses reported in the following text are those yielding the smallest factor of safety at any given location.

7.1 Design Conditions - Tubes Fixed

The maximum general primary membrane occurs at location 15. Its value is 8.3 KSI compared to its limit 15 KSI.

The primary membrane plus primary bending is exceeded at the inside of locations 1 and 16. The respective values are 25.6 KSI and 23.9 KSI compared to a limit of 22.5 KSI. This is considered to be acceptable however, since in the final manufacture of the connector region, the additional material on the inside and outside of the connector from locations 1 to 16 (Figure 2) will actually all be placed on the inside for purposes of forging procedures. This is expected to bring the stresses within allowable limits due to additional thickness on the inside.

7.2 Design Conditions - Tubes Free

The maximum general primary membrane occurs at location 16. Its value is 6.2 KSI compared to its limit 15.0 KSI.

The maximum primary membrane plus primary bending occurs at the outside of location 16. Its value is 19.4 KSI compared to its limit 22.5 KSI.

7.3 Steady State - Tubes Fixed

The maximum general primary membrane occurs at location 51. Its value is 7.7 KSI compared to its limit 17.9 KSI.

The maximum primary membrane plus primary bending occurs at the inside of location 1. Its value is 22.2 KSI compared to its limit 26.9 KSI.

To ensure freedom from ratchetting and excessive deformation, the range of primary plus secondary stress intensities must be checked. The maximum value occurs at the outside of location 91. Its value is 22.6 KSI compared to its limit 24.5 KSI.

7.4 Steady State - Tubes Free

The maximum general primary membrane occurs at location 16. Its value is 6.2 KSI compared to its limit 17.9 KSI.

The maximum primary membrane plus primary bending occurs at the outside of location 16. Its value is 17.9 KSI compared to its limit 26.9 KSI.

Again, to ensure freedom from ratchetting and excessive deformation, the range of primary plus secondary stress intensity must be checked. The maximum value occurs at the outside of location 91. Its value is 19.3 KSI compared to its limit 24.5 KSI.

8.0 Conclusions and Recommendations

From the foregoing preliminary analysis, the structural integrity of the connector region for the evaporator has been found marginal for design conditions and acceptable for steady-state. Since the connector will never see the design loads imposed and since a final detailed elastic-plastic analysis would most likely assure its integrity under design conditions, this connector is considered adequate for the evaporator. This connector also results in acceptable tube loads. The interchangeability of the evaporator connector with the superheater connector must be assured at a later date due to the high temperature of the superheater.

TYPE JOB	LOAD CONTROLLED	DEFORMATION CONTROLLED
Job #	1714	1231
δ_{zo} (in)	0.	0.
δ_{no} (in)	0.	-.1339
δ_{mo} (rds)	0.	0.
F_{zn} (lbs)	3.353×10^5	1.4979×10^6
δ_{rn} (in)	0.	.3124
δ_{mn} (rds)	0.	0.
P_i (psi)	300.	300.
E (psi)	26.0×10^6	26.0×10^6
G (psi)	10.0×10^6	10.0×10^6
α (in/in-°F)	7.6×10^{-6}	7.6×10^{-6}
μ	.3	.3
T_o (°F)	0.	650.
T_n (°F)	0.	890.

Table 1
Boundary Values for Design Conditions
with the Tubes Fixed

TYPE JOB	LOAD CONTROLLED	DEFORMATION CONTROLLED
Job #	1684	1250
δ_{zo} (in)	0.	0.
δ_{no} (in)	0.	-.1339
δ_{mo} (rds)	0.	0.
F_{zn} (lbs)	1.8124×10^6	1.1968×10^6
δ_{rn} (in)	0.	.3124
δ_{mn} (rds)	0.	0.
P_i (psi)	300.	300.
E (psi)	26.0×10^6	26.0×10^6
G (psi)	10.0×10^6	10.0×10^6
α (in/in- $^{\circ}$ F)	7.6×10^{-6}	7.6×10^{-6}
μ	.3	.3
T_o ($^{\circ}$ F)	0.	650.
T_n ($^{\circ}$ F)	0.	890.

Table 2
Boundary Values for Design Conditions
with the Tubes Free

TYPE JOB	LOAD CONTROLLED	DEFORMATION CONTROLLED
Job #	1715	1258
δ_{zo} (in)	0.	0.
δ_{no} (in)	0.	-.1315
δ_{mo} (rds)	0.	0.
F_{zn} (lbs)	2.9383×10^5	1.3085×10^6
δ_{rn} (in)	0.	.2998
δ_{mn} (rds)	0.	0.
P_i (psi)	260.	260.
E (psi)	26.4×10^6	26.4×10^6
G (psi)	10.15×10^6	10.15×10^6
α (in/in - $^{\circ}F$)	7.55×10^{-6}	7.55×10^{-6}
μ	.3	.3
T_o ($^{\circ}F$)	0.	610.
T_n ($^{\circ}F$)	0.	858.

Table 3
Boundary Values for Steady-State
Conditions with the Tubes Fixed

TYPE JOB	LOAD CONTROLLED	DEFORMATION CONTROLLED
Job #	1718	1272
δ_{zo} (in)	0.	0.
δ_{no} (in)	0.	-13.15
δ_{mo} (rds)	0.	0.
F_{zn} (lbs)	1.5758×10^6	1.1673×10^6
δ_{rn} (in)	0.	.2998
δ_{mn} (rds)	0.	0.
P_i (psi)	260.	260.
E (psi)	26.4×10^6	26.4×10^6
G (psi)	10.15×10^6	10.15×10^6
α (in/in - $^{\circ}\text{F}$)	7.55×10^{-6}	7.55×10^{-6}
μ	.3	.3
T_o ($^{\circ}\text{F}$)	0.	610.
T_n ($^{\circ}\text{F}$)	0.	858.

Table 4
Boundary Values for Steady-State
Conditions with the Tubes Free

DESIGN CONDITIONS - TUBES FIXED

LOC	COMP	P _m	S _o	P _b Outside	P _b Inside	P _m + P _b Outside	P _m + P _b Inside	1.5 S _o
1	TXY	-.4	15.0	-21.0	21.0	-16.5	25.5	22.5
	SX	4.5						
	SO	4.0						
	SY	-.1						
	2TMAX	4.7						
16	TXY	-.3	15.0	-16.9	16.9	-10.0	23.8	22.5
	SX	6.9						
	SO	-.9						
	SY	-.1						
	2TMAX	7.8						
51	TXY	-.1	15.0	9.5	-9.7	13.9	-5.3	22.5
	SX	4.4						
	SO	-3.9						
	SY	-.1						
	2TMAX	8.3						
91	TXY	-.5	13.9	-8.3	8.2	-4.9	11.6	20.9
	SX	3.4						
	SO	4.2						
	SY	-.2						
	2TMAX	4.5						
100	TXY	-.2	13.4	-9.9	9.9	-7.4	12.4	20.1
	SX	2.5						
	SO	.4						
	SY	-.2						
	2TMAX	2.7						

Table 5

Design Stresses - Tubes Fixed

DESIGN CONDITIONS - TUBES FREE

LOC	COMP	P _m	S _o	P _b Outside	P _b Inside	P _m + P _b Outside	P _m + P _b Inside	1.5 S _o
1	TXY	-.6	15.0	7.3	-7.3	-6	-6	22.5
	SX	3.3						
	SO	3.6						
	SY	-.1						
	2TMAX	3.8						
16	TXY	-.5	15.0	14.2	-14.2	-5	-5	22.5
	SX	5.1						
	SO	-1.1						
	SY	-.1						
	2TMAX	6.2						
51	TXY	-.1	15.0	-8.0	8.2	-.1	-.1	22.5
	SX	3.2						
	SO	-1.3						
	SY	-.1						
	2TMAX	4.5						
91	TXY	-.4	13.9	5.9	-5.9	-.4	-.4	20.9
	SX	2.7						
	SO	4.3						
	SY	-.2						
	2TMAX	4.6						
100	TXY	-.1	13.4	5.3	-5.3	-.1	-.1	20.1
	SX	2.0						
	SO	2.6						
	SY	-.2						
	2TMAX	2.8						

Table 6

Design Stresses - Tubes Free

STEADY STATE - TUBES FIXED

LOC	COMP	P _m	S _{mt}	S _m S _t	P _L S _t	K	P _b Outside	P _b Inside	P _L + P _b Outside	P _L + P _b Inside	1.5 S _m KS _t
1	TXY	-.4		17.9					-.4	-.4	26.9
	SX	4.0					-18.2	18.1	-14.2	22.1	
	SO	4.5					-5.4	5.4	-.9	9.9	
	SY	-.1							-.1	-.1	
	2TMAX	4.6	17.9	35.5	.13	1.22			14.1	22.2	43.3
16	TXY	-.2		17.9					-.2	-.2	26.9
	SX	6.2					-14.6	14.6	-8.4	20.8	
	SO	-.7					-5.8	5.8	-6.5	5.1	
	SY	-.1							-.1	-.1	
	2TMAX	6.9	17.9	35.5	.19	1.20			8.3	20.9	42.6
51	TXY	-.1		17.9					-.1	-.1	26.9
	SX	3.9					8.2	-8.4	12.1	-4.5	
	SO	-3.8					2.2	-2.2	-1.6	-6.0	
	SY	-.1							-.1	-.1	
	2TMAX	7.7	17.9	26.6	.29	1.18			13.7	5.9	31.4
91	TXY	-.5		17.7					-.5	-.5	26.6
	SX	2.9					-7.1	7.1	-4.2	10.0	
	SO	4.6					-2.1	2.1	2.5	6.7	
	SY	-.2							-.2	-.2	
	2TMAX	4.9	13.6	13.3	.37	1.16			6.6	10.2	15.4
100	TXY	-.3		17.5					-.3	-0.3	26.3
	SX	2.1					-8.5	8.5	-6.4	10.6	
	SO	.7					-2.5	2.5	-1.8	3.2	
	SY	-.2							-.2	-.2	
	2TMAX	2.4	11.9	11.8	.20	1.20			6.2	10.8	14.2

Table 7

Steady State Stresses - Tubes Fixed

STEADY STATE - TUBES FIXED

LOC	COMP	P _L	P _{b/K} Outside	P _{b/K} Inside	Q Outside	Q Inside	P _L + P _{b/K} + Q Outside	P _L + P _{b/K} + Q Inside	1.25 S _t S _y
1	TXY	-.4					-.4	-.4	44.4
	SX	4.0	-14.9	14.8	9.0	-9.0	-1.9	9.8	
	SO	4.5	-4.4	4.4	2.8	-2.4	2.9	6.5	
	SY	-.1					-.1	-.1	
	2TMAX						4.9	9.9	26.5
16	TXY	-.2					-.2	-.2	44.4
	SX	6.2	-12.2	12.2	4.8	-4.7	-1.2	13.7	
	SO	-.7	-4.8	4.8	2.1	-2.1	-3.4	2.0	
	SY	-.1					-.1	-.1	
	2TMAX						3.3	13.8	26.5
51	TXY	-.1					-.1	-.1	38.0
	SX	3.9	6.9	-7.1	-11.5	11.7	-.7	8.5	
	SO	-3.8	1.9	-1.9	-4.5	4.6	-6.4	-1.1	
	SY	-.1					-.1	-.1	
	2TMAX						6.3	9.6	26.5
91	TXY	-.5					-.5	-.5	24.5
	SX	2.9	-6.1	6.1	25.6	-25.6	22.4	-16.6	
	SO	4.6	-1.8	1.8	7.6	-7.6	10.4	-1.2	
	SY	-.2					-.2	-.2	
	2TMAX						22.6	16.4	26.2
100	TXY	-.3					-.3	-.3	22.1
	SX	2.1	-7.1	7.1	24.2	-24.1	19.2	-14.9	
	SO	.7	-2.1	2.1	7.2	-7.3	5.8	-4.5	
	SY	-.2					-.2	-.2	
	2TMAX						19.4	14.7	26.0

Table 8

Steady State Stresses - Tubes Fixed

STEADY STATE - TUBES FREE

LOC	COMP	P _m	S _{mt}	S _m / S _t	P _L / S _t	K	P _b Outside	P _b Inside	P _L + P _b Outside	P _L + P _b Inside	1.5 S _m / K S _t
1	TXY	-.4		17.9					-.4	-.4	26.9
	SX	3.4					6.4	-6.4	9.8	-3.0	
	SO	4.5					1.9	-2.0	6.4	2.5	
	SY	-.1							-.1	-.1	
	2TMAX	4.6	17.9	35.5	.13	1.22			9.9	5.6	43.3
16	TXY	-.3		17.9					-.3	-.3	26.9
	SX	5.4					12.4	-12.4	17.8	-7.0	
	SO	-.8					4.6	-4.6	3.8	-5.4	
	SY	-.1							-.1	-.1	
	2TMAX	6.2	17.9	35.5	.17	1.21			17.9	6.9	43.0
51	TXY	-.1		17.9					-.1	-.1	26.9
	SX	3.3					-7.0	7.2	-3.7	10.5	
	SO	-2.6					-1.8	1.8	-4.4	-.8	
	SY	-.1							-.1	-.1	
	2TMAX	5.9	17.9	26.6	.22	1.20			4.3	11.3	31.9
91	TXY	-.4		17.7					-.4	-.4	26.6
	SX	2.6					5.1	-5.1	7.7	-2.5	
	SO	4.5					1.6	-1.6	6.2	3.0	
	SY	-.2							-.2	-.2	
	2TMAX	4.9	13.6	13.3	.37	1.16			7.9	5.6	15.4
100	TXY	-.2		17.5					-.2	-.2	26.3
	SX	1.9					4.7	-4.7	6.6	-2.8	
	SO	.6					1.4	-1.4	2.0	-.8	
	SY	-.2							-.2	-.2	
	2TMAX	2.1	11.9	11.8	.18	1.21			6.8	2.6	14.3

Table 9

Steady State Stresses - Tubes Free

STEADY STATE - TUBES FREE

LOC	COMP	P_L	P^b/K Outside	P^b/K Inside	Q Outside	Q Inside	$P_L + P^b/K$ + Q Outside	$P_L + P^b/K$ + Q Inside	$1.25 S_t$ S_y
1	TXY	-.4					-.4	-.4	44.4
	SX	3.4	5.2	-5.2	-18.2	18.3	-9.6	16.5	
	SO	4.5	1.6	-1.6	-5.5	5.7	.6	8.6	
	SY	-.1					-.1	-.1	
	2TMAX						10.2	16.6	26.5
16	TXY	-.3					-.3	-.3	44.4
	SX	5.4	10.2	-10.2	-25.2	25.2	-9.6	20.4	
	SO	-.8	3.8	-3.8	-9.4	9.5	-6.4	4.9	
	SY	-.1					-.1	-.1	
	2TMAX						9.5	20.5	26.5
51	TXY	-.1					-.1	-.1	38.0
	SX	3.3	-5.8	6.0	5.4	-5.6	2.9	3.7	
	SO	-2.6	-1.5	1.5	-.1	.2	-4.2	-.9	
	SY	-.1					-.1	-.1	
	2TMAX						7.1	4.6	26.5
91	TXY	-.4					-.4	-.4	24.5
	SX	2.6	4.4	-4.4	12.1	-12.0	19.1	-13.8	
	SO	4.6	1.4	-1.4	3.5	-3.5	9.5	-.3	
	SY	-.2					-.2	-.2	
	2TMAX						19.3	13.6	26.2
100	TXY	-0.2					-.2	-.2	22.1
	SX	1.9	3.9	-3.9	9.5	-9.5	15.3	-11.5	
	SO	.6	1.2	-1.2	2.9	-2.9	4.7	-3.5	
	SY	-.2					-.2	-.2	
	2TMAX						15.5	11.3	26.0

Table 10

Steady State Stresses - Tubes Free

Figure 1
Double Tubesheet Connector Configuration

T_o Operating

Figure 3

Mathematical Model

NOTE: Subscripts used in text are shown for various elements.

Figure 4

Interaction Model - Tubes Fixed

NOTE: Subscripts used in text are shown for various elements.

Figure 5
Interaction Model - Tubes Free

Figure 6
Steady State Temperatures
(From Reference 4)

9.0 References

1. American Society of Mechanical Engineers, "Interpretations of ASME Boiler and Pressure Vessel Code, Code Case 1331-8, Nuclear Components in Elevated Temperature Service", December 19, 1972.
2. Friedrich, C. M., "Seal-Shell-2-A Computer Program for the Stress Analysis of a Thick Shell of Revolution with Axisymmetric Pressures, Temperatures, and Distributed Loads", WAPD-TM-398, Addendum II, June 1974.
3. Flury, R. L., "Superheater Duplex Tube Steady State Analysis Demonstrating 2½Cr-1Mo as an Acceptable Reference Material, "Work Performed for USAEC Under Contract AT(04-3)-962 Task 6, June 1974.
4. Letter, R. P. Waszink to W. Rinne, "Task 7 U-Bend Effectiveness Study - Evaporator Performance", May 14, 1974.

11: ATTACHMENT:

MATERIAL PROPERTIES AND
STRENGTH LIMITS FOR
2 1/4 CR-1 MO

MODULUS OF ELASTICITY, 10⁶ PSI

30

25

20

15

10

0

200

400

600

800

1000

1200

TEMPERATURE, °F

TABLE 21
CODE CASE 1331-8
DATA PACKAGE

COINCIDES WITH VALUES FROM
SECTION III TABLE I-6.0 FOR
RT ≤ T ≤ 700 °F

FIGURE A-1 TENSILE MODULUS OF ELASTICITY OF 2 1/4 CR-1 MD
FOR BOTH LOW AND HIGH TEMPERATURE APPLICATION

(14)

FIGURE A-2 RECOMMENDED 2 1/4 CR-LMO THERMAL EXPANSION COEFFICIENTS FOR BOTH LOW- AND HIGH-TEMPERATURE APPLICATION

0.7
3.0/2