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AEC Research and
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UC-81, Reactors - Power
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detailed stress analysis of SM-1
steam generator tube sheet

Contract No. AT[30-1]-2639
with U. S. Atomic Energy Commission
New York Operations Office

ALCO PRODUCTS, INC.
NUCLEAR POWER ENGINEERING DEPARTMENT

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APAE Memo-319

AEC Research and
Development Report
UC-81, Reactors, Power
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DETAILED STRESS ANALYSIS OF
SM-1 STEAM GENERATOR TUBE SHEET

By:

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Approved By:

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Issued: July 11, 1962

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with U.S. Atomic Energy Commission
New York Operations Office

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ABSTRACT

The detailed stress analysis of the SM-1 steam generator tube sheet showed it to be safe from strain cycling damage. However, the pressure stresses were greater than the yield strength during the hydrostatic test. The differential between pressure stresses and yield strength indicates that some initial deformation may have taken place in the tube sheet.

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SUMMARY

The three major cyclic conditions considered in this stress analysis of the SM-1 steam generator tube sheet revealed no problem caused by strain cycling damage (Fig.1). Conditions were evaluated as specified in the Navy Code⁽¹⁾ and are listed as follows:

<u>Condition</u>	<u>Allowable Cycles</u>	<u>Estimated⁽²⁾ Plant Cycles</u>
a) Startup and Shutdown Cycle	2,500	900
b) Loss of Load	100,000	1,500
c) Hydrostatic Test	100	20

The pressure stresses are greater, however, during the hydrostatic testing and the startup cycle than the limits specified in a paper by O'Donnell and Langer "Design of Perforated Plates".⁽⁴⁾ This fact indicates that deformation may occur in the tube sheet. Although this plant has been hydro-tested approximately 5 to 10 times, there has been no evidence of leakages from primary to secondary. To minimize deformations in the tube sheet, the plant during future primary system hydrostatic tests should have full pressure on the secondary side.

It should also be noted that the original design procedures were those normally used for equipment of this type as defined in TEMA standards. The more sophisticated analysis presented here is based on elastic theory and does not take into account the re-distribution of stress which takes place after initial yielding has occurred. Since the initial yielding (which probably took place during the first hydro-static test) resulted in no leaks or other difficulty and no hazard exists from the fatigue standpoint, continued safe operation can be expected as in the case of other similar vessels designed to the TEMA standards as was the SM-1 steam generator.

Figure 1. Fatigue Diagram of SM-1 Steam Generator Tube Sheet

DETAILED STRESS ANALYSIS OF SM-1 STEAM GENERATOR TUBE SHEET

1.0 INTRODUCTION

This report presents a detailed stress and fatigue analysis of the SM-1 steam generator tube sheet. A stress analysis of the SM-1 primary system was previously reported in APAE Memo-283, ⁽²⁾ which recommended that the tube sheet be studied in greater detail than afforded by preliminary analysis. The method of analysis used in APAE Memo-283 for the tube sheet was a simple modification of a solid circular plate, and stresses did not necessarily represent worse case conditions because of the highly complex geometry of the tube sheet.

Work was performed under Subtask 1.1 of the Army PWR Support and Development Program.

2.0 METHOD OF ANALYSIS

Calculation of stresses in perforated plates has received considerable attention as a result of wider use of flat tube sheets in heat exchanger equipment. The method for analyzing perforated plates involves the concept of an equivalent solid plate with the same dimensions as the actual plate; but, either the flexural rigidity of the solid plate is reduced (by a factor called its deflection efficiency) ⁽³⁾ or fictitious elastic constants ⁽⁴⁾ (E^* ν^*) are used in place of the actual constants of the material (E and ν).

Because the perforated plate is part of a structure, the classical structural analysis method is used, ⁽⁵⁾ with the correction factor (for the perforated plate) in the form of an efficiency or the introduction of the fictitious elastic constants. The paper by Yi-Yuan Yu, ⁽⁶⁾ which incorporates the Gardner and Miller ⁽³⁾ correction factor was compared to the paper by O'Donnell and Langer ⁽⁴⁾ which incorporates the fictitious elastic constants. The latter analysis was chosen because it is more detailed.

3.0 STRESS AND FATIGUE ANALYSIS

The peak stress in the steam generator tube sheet, resulting from pressure alone, is located in the ligaments; and this maximum stress occurs during the hydrostatic test of the primary coolant system. The pressure on the primary system during this test is 2250 psig (1.5 x design pressure) and the pressure on the secondary side is atmospheric. Both primary and secondary sides are at the same temperature; therefore, no thermal stress is imposed.

The cyclic stress for the startup and shutdown cycle (ambient to full power primary and secondary) is more severe than the loss of load cycle (full power on primary and secondary with complete loss of load). The former condition (start-up and shutdown cycle) imposed a differential pressure of 1000 psi (1200 psig primary and 200 psig secondary) while the latter imposed a differential pressure of 756 psi (1200 psig primary and 444 psig secondary). The thermal stresses superimposed on the peak pressure stresses are in the order of 10 percent.

The tube sheet stress analysis is developed without complete knowledge as to whether this perforated plate is a classical, simply supported plate or a clamped-edge-type plate. With the aid of "Theory of Plates and Shells" (5) and the O'Donnell and Langer paper, (4) the results from the application of the equations show the tube sheet to be very close to a clamped edge. See (Fig.2.)

In a pure clamped-edge plate analysis, the sign of both the σ_θ and σ_r must change as the point under consideration moves from $r = 0$ to $r = a$, while in a simply supported plate analysis, the sign remains the same (Fig.2). In the clamped-edge case, the sign changes, and the value of $|\sigma_{\max}|$ solved for by the use of the classical equations (independent of the factor used for the perforation) is equal to $|\sigma_r|$, because the maximum stress on the flat plate under study is located at the edge. Now if $|\sigma_{\max}|$ or $|\sigma_r|$ equals $-3/4 \frac{qa^2}{h^2}$ (Fig.2, SM-1 Stress Analysis), we have a pure, clamped-edge tube sheet. In this particular case the difference is approximately (1 to 3 percent), which, for all practical purposes, describes this tube sheet as a clamped edge.

4.0 CONCLUSION

(Refer to Table 1.) The stresses due to pressure alone exceed the limits specified during normal operation by 18 percent, and during the hydrostatic test by 120 percent. The yield strength of this material is 38,000 psi and this is not exceeded during normal operation. During the hydrostatic test, however, the yield strength is exceeded.

The hydrostatic conditions imposed upon the tube sheet are evidently beyond the limitations of this analysis because this plant has undergone approximately 5 to 10 hydrostatic tests on the primary system and has been in operation without apparent leakage. However, as mentioned above, the pressure stresses imposed during the primary system hydrostatic test and during the startup and shutdown cycle exceed the O'Donnell and Langer (4) criteria of limits. In future designs, it is recommended that the O'Donnell (3) criteria of limits be complied with and that during primary system hydrostatic tests, after code requirements are met (1.5 design pressure), the hydrostatic test be performed with full pressure on the secondary side to minimize the differential pressure and reduce the pressure stress magnitude. This recommendation should not be considered as superseding any limitations which may be imposed by radiation damage criteria in the reactor vessel itself, which may be the controlling factor in hydrostatic testing of the primary system as a whole.

where: ν = Poisson's Ratio
 $q = \Delta P$ (Primary Pressure - Secondary Pressure)
 h = Tube Sheet Thickness
 a = Plate Radius
 σ = Stress Intensity
 θ = Edge Rotation
 r = Radial Co-ordinate

Figure 2. Stress Analysis Schematic, SM-1 Tube Sheet

(From "Theory of Plates and Shells" Timoshenko, Page 61)

TABLE 1
STRESS SUMMARY

Load	Stress Intensity (Type and Location)	Full Load to No Load Stress Intensity	Startup Cycle Stress Intensity	LIMIT	Hydro Primary Stress Intensity
Pressure	Average across ligament at either surface	27,500	35,300	← 30,000 35,600 →	79,000
	Average across ligament through thickness			← 20,000 23,700 →	
Combined Press. and Thermal	Average across ligament at either surface	41,420	49,220	← 60,000 71,000 →	79,000
Combined Press. and Thermal	Peak in ligaments	49,226	64,670	-	136,650
	Peak at perforations adjacent to rim	18,200	23,400	-	-
Cyclic Thermal Skin Effect	Peak at surface	13,920	13,920	-	-
Cyclic Thermal Temperature Dif- ferential Across Diametrical Lane	Peak in ligaments	3,470	3,470	-	-
	Peak at holes adjacent to diametrical lane	4,370	4,370	-	-

Figure 3. Diagram of SM-1 Steam Generator Tube Sheet

NOTE:
 DRILL & RE-AM - THE 720 HOLES AND TUBES.
 HOLES MAY BE DRILLED BUT DO NOT RE-AM UNTIL
 ADVISED BY THE T.O. OFFICE. THE TUBES IN
 BUNDLE NO. 5 WILL TURN BE REAMED TO .009" T.O.D.
 LARGER IN DIA. THAN THE 3" DIA. TUBES IN THE
 BUNDLE.

12 TUBE HOLES MARKED THIS
 TO BE PLUGGED PER C-152367

94 HOLES SHOWN THIS ON MARKED-UP
 BLUEPRINT OF DWG. E-146646 ARE TO BE
 FILLED WITH WELD METAL BEFORE ANY
 ADDITIONAL DRILLING IN TUBE SHEET IS
 DONE

ALCO		ALCO PRODUCTS, INCORPORATED PLANT NO. 2 DUNKIRK, NEW YORK	
39" TUBE LAYOUT			
2-PASS 39" O.D. U-TUBES 1" TRI. PITCH			
APPROVED	SCALE	MADE	CHECKED
43058	6"=1'-0"	ALP.	H.
ITEM	DATE	CERTIFIED	DRAWING NO.
	5/31/62	H.	H-152400

The fatigue analysis (Fig.2) based on the Navy Code⁽¹⁾ shows the tube sheet to be safe from strain cycling damage during startup cycle, loss of load cycle, and hydrostatic test cycle.

5.0 REFERENCES

1. Tentative Structural Design Basis for Reactor Pressure Vessels and Directly Associated Components, " Office of Technical Services, Bulletin PB-151987, December 1, 1958, Revision.
2. Chittum, R.A., McLaughlin, D.W., Knipe, R.K., "Preliminary Stress and Fatigue Analysis of the SM-1 Primary System," APAE Memo 283, March 31, 1962.
3. Gardner, K.A., "Heat Exchanger Tube Sheet Design," "Journal of Applied Mechanics," December 1948.
4. O'Donnell, W.J., and Langer, B.F., "Design of Perforated Plates," ASME Paper 61-WA-115, January 1962.
5. Timoshenko, S., "Theory of Plates and Shells," McGraw-Hill Book Co., Inc., New York, 1940.
6. Yi-Yuan Yu, "Rational Analysis of Heat-Exchanger Tube-Sheet Stresses," "Journal of Applied Mechanics," September 1956.

6.0 APPENDIX

The appendix comprises calculations, Sheets 1-6, from several independent sources. These calculations support the conclusions reached in this report.

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BY J.J.B. DATE 1/25/62 SUBJECT _____
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SHEET NO. 1 OF _____
 JOB NO. _____

Operating Press.

Tube side	1200
Shell side, Full load, psia	200
Shell side, No load, psia	122.6

Design pressure

Tube side, psia	1500
Shell side, psia	500

Operating temperatures

Pr. Coolant inlet, full load, °F	450
" " outlet, " " "	431.6
Feedwater inlet, °F	246.1
Steam outlet, Full load	407.0
Steam outlet, No load	450.

Design temperatures

Tube side °F	650
Shell side °F	650

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BY RAC DATE 1/15/62 SUBJECT SM-1 STEAM SHEET NO. 2 OF 2
 CHKD. BY DATE GENERATOR TUBE SHEET JOB NO. Sub-Task 1.1

The following analysis is from Journal of Applied Mechanics, Sept 1956, "Rational Analysis of Heat Exchanger Tube Sheet Stresses" by Yi-Yuan Yu.

$$M_r = \frac{(3+\nu)qr^2}{16} + D(1+\nu) \frac{C_1}{2}$$

$$C_1 = \frac{2(K_h \theta_h - K_s \theta_s)}{D(1+\nu) + a(K_s + K_h + K_f)} - \frac{qa^2}{8D} \left[\frac{D(3+\nu) + a(K_s + K_h + K_f)}{D(1+\nu) + a(K_s + K_h + K_f)} \right]$$

$$D = \frac{Eh^3 \eta_w}{12(1-\nu^2)}$$

$$\eta_w = .5 \left(1 - .952 \frac{d}{P} \right)$$

$$\theta_s = \frac{(3)^{1/4} (1-\nu_s^2)^{1/4} P_s \left(\frac{a'}{t_s} \right)^{3/2}}{E_s}$$

$$\theta_s = \frac{1.285 P_s}{E_s} \left(\frac{a'}{t_s} \right)^{3/2}$$

$$\theta_h = \frac{(3)^{1/4} (1-\nu_h^2)^{1/4} P_h \left(\frac{a'}{t_h} \right)^{3/2}}{E_h}$$

$$\theta_h = \frac{1.285 P_h}{E_h} \left(\frac{a'}{t_h} \right)^{3/2}$$

$$K_s = \frac{E_s (t_s)^{5/2}}{2 \times 3^{3/4} (1-\nu_s^2)^{3/4} (a')^{1/2}} = \frac{E_s (t_s)^{5/2}}{4.25 (a')^{1/2}}$$

$$K_h = \frac{E_h (t_h)^{5/2}}{2 \times 3^{3/4} (1-\nu_h^2)^{3/4} (a')^{1/2}} = \frac{E_h (t_h)^{5/2}}{4.25 (a')^{1/2}}$$

where:

E = Mod. of Elast.
 h = Tube Sheet Thickness
 η_w = Deflection Eff.
 q = Uniform pressure
 a = Plate radius
 a' = Shell radius
 D = Flexural rigidity
 K = Rotation stiffness
 θ = Edge rotation
 d = Outside tube dia
 P = Tube Pitch

Subscripts s & h refer to Shell & head.

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SHEET NO. 3 OF _____

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Normal Operating Conditions :

Secondary : $P = 444$ psi
 $T = 455^{\circ}F$

Primary : $P = 1200$ psi
 $T = 450^{\circ}F$

From Navy Code:

$$E_s \& E_h = 27.2 \times 10^6$$

$$\alpha_s \& \alpha_h = 6.9 \times 10^{-6}$$

$$D = \frac{Eh^3 \eta_w}{12(1-\nu^2)}$$

$$\eta_w = .5 \left(1 - .952 \frac{d}{p} \right)$$

$$\eta_w = .5 \left[1 - .952 \left(\frac{.75}{1} \right) \right] = .143$$

$$d = \frac{3}{4}''$$

$$p = 1'' \text{ pitch}$$

$$\nu = .3$$

$$D = \frac{27.2 \times 10^6 (5.5)^3 (.143)}{12(1-.09)} = 59.26 \times 10^6$$

$$\theta_s = \frac{1.285 P_s}{E_s} \left(\frac{a'}{t_s} \right)^{3/2} = \frac{1.285 (444)}{27.2 \times 10^6} \left(\frac{22.8125}{.8125} \right)^{3/2} = 3.20 \times 10^{-6}$$

$$\theta_h = \frac{1.285 P_h}{E_h} \left(\frac{a'}{t_h} \right)^{3/2} = \frac{1.285 (1200)}{27.2 \times 10^6} \left(\frac{22.8125}{4.75} \right)^{3/2} = 5.95 \times 10^{-6}$$

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SHEET NO. 4 OF _____

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$$K_s = \frac{E_s (t_s)^{5/2}}{4.25 (a')^{1/2}} = \frac{27.2 \times 10^6 \cdot (.8125)^{5/2}}{4.25 (22.8125)^{1/2}} = 0.8 \times 10^6$$

check $\rightarrow$ $K_h = \frac{E_h (t_h)^{5/2}}{4.25 (a')^{1/2}} = \frac{27.2 \times 10^6 (4.75)^{5/2}}{4.25 (22.8125)^{1/2}} = 65.7 \times 10^6$

$$C_1 = \frac{2(K_h \theta_h - K_s \theta_s)}{D(1+\nu) + a(K_s + K_h + K_f)} \quad \frac{gr^2}{9D} \left[\frac{D(3+\nu) + a(K_s + K_h + K_f)}{D(1+\nu) + a(K_s + K_h + K_f)} \right]$$

$$C_1 = \frac{2[(65.7 \times 10^6)(595 \times 10^6) - (.8 \times 10^6)(3124 \times 10^{-6})]}{59.26(1.3) + 11875(.8 \times 10^6 + 65.7 \times 10^6)}$$

$$= \frac{756(18.875)^2}{8(59.26 \times 10^6)} \left[\frac{59.26(3.3) + 11875(.8 \times 10^6 + 65.7 \times 10^6)}{59.26(1.3) + 11875(.8 \times 10^6 + 65.7 \times 10^6)} \right]$$

$$C_1 = \frac{73750}{1330} - 567.7 \times 10^{-6} \left(\frac{1449}{1330} \right) = -564 \times 10^{-6}$$

$$M_r = \frac{(3+\nu)gr^2}{16} + D(1+\nu)\frac{C_1}{2}$$

r - radial coordinate

@ Tube Sheet Center (r=0):

$$M_r = 59.26 \times 10^6 (1.3) \left(-\frac{564 \times 10^{-6}}{2} \right) = -21,725$$

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@ Tube Sheet Edge ($r = a$):

$$M_r = \frac{3.3 (756)(18.875)^2}{16} - 21725 = 55,600 - 21,725$$

$$M_r = 33,875$$

$$\sigma_{\max} = \frac{6 M_r}{h^2 \eta_{\sigma}} = \frac{6 (33,875)}{(5.527)^2} = \frac{6718}{\eta_{\sigma}}$$

 η_{σ} = ligament efficiency

$$\begin{aligned} \eta_{\sigma} \text{ (by Gardner)} &= 1 - \frac{3}{\pi} \sin^{-1} \left(\frac{r}{2} \right) = \\ &= 1 - \frac{3}{\pi} \sin^{-1} [(0.707)(.75)] \\ &= 1 - \frac{3}{\pi} \sin^{-1} (.53) = 1 - \frac{3}{\pi} \sin^{-1} 32^\circ \\ &= 1 - \frac{3}{\pi} \frac{32 \pi}{180} = .466 \end{aligned}$$

$$\begin{aligned} \eta_{\sigma} \text{ (by Miller)} &= 1 - \frac{\pi \sqrt{3}}{6} \frac{d^2}{p^2} = 1 - \frac{\pi \sqrt{3}}{6} (.563) \\ &= .490 \end{aligned}$$

$$\therefore \sigma_{\max} = \frac{6718}{.466} = 14,395 \text{ psi (by Gardner)}$$

@ edge

$$\sigma_{\max} = \frac{6718}{.49} = 13,690 \text{ psi (by Miller)}$$

@ edge

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 SHEET NO. 6 OF _____

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The following Analysis is by ASME paper 61-WA-115
 "Design of Perforated Plates" by W.J. O'Donnell & B.F. Langer.

$$h/R = .25$$

From fig. 5 of "Design of Perforated Plates":

$$E^*/E = .19$$

$$\nu^* = .425$$

$$E^* = .19(27.2 \times 10^6) = 5.16 \times 10^6$$

$$D^*/D = .21$$

$$D^* = \frac{E^* H^3}{12(1-\nu^{*2})} = \frac{5.16 \times 10^6 (5.5)^3}{12[1-(.425)^2]} = 87.4 \times 10^6$$

$$C_1^* = \frac{2(K_n \theta_n - K_s \theta_s)}{D^*(1-\nu^*) + a(K_s + K_n)} - \frac{9a^2}{8D^*} \left[\frac{D^*(3+\nu^*) + a(K_s + K_n)}{D^*(1+\nu^*) + a(K_s + K_n)} \right]$$

$$C_1^* = \frac{2[(65.7 \times 10^6)(592 \times 10^{-6}) - (.8 \times 10^6)(500 \times 10^{-6})]}{87.4 \times 10^6 (1.425) + 18.875(65.7 \times 10^6 + 0.8 \times 10^6)}$$

$$- \frac{756(18.875)^2}{8(87.4 \times 10^6)} \left[\frac{87.4 \times 10^6 (3.425) + 18.875(.8 \times 10^6 + 65.7 \times 10^6)}{87.4 \times 10^6 (1.425) + 18.875(.8 \times 10^6 + 65.7 \times 10^6)} \right]$$

$$C_1^* = \frac{73440}{1379.7 \times 10^6} - 3852 \times 10^{-6} (1.1266)$$

$$C_1^* = 53.2 \times 10^{-6} - 4339.8 \times 10^{-6} = -4287 \times 10^{-6}$$

$$= -220.9 \times 10^{-6}$$

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$$M_r = \frac{(3+\nu^*)}{16} q r^2 + D^* (1+\nu^*) \frac{C_1}{2}$$

@ Tube Sheet center ($r=0$)

$$M_\theta = M_r = 87.4 \times 10^6 (1.425) \left(-\frac{.00429}{2} \right) = -22,726$$

@ Tube Sheet edge ($r=R$)

$$M_r = \frac{3.425}{16} (756) (18.875) - 22,726$$

$$M_r = 57,600 - 22,726 = 34,874$$

$$\sigma_{max} = \frac{6(33870)}{(5.5)^2} = 6,720 \text{ psi @ Tube Sheet edge}$$

$$M_{ra} = \frac{q}{16} [a^2(1+\nu)^2 - 3 - \nu] \quad \text{+ From theory of Plates & Shells}$$

Page # 61 & 62

$$= -\frac{q a^2}{8}$$

$$\sigma_r = \frac{6M_r}{h^2} = -\frac{3}{4} q \frac{a^2}{h^2} = -6,720 \text{ psi}$$

$$\sigma_\theta = \sigma_r - (1-\nu^*) \cdot \frac{3}{4} q \frac{a^2}{h^2}$$

$$\sigma_r = .575 \times .75 \times 756 \left(\frac{18,875}{5.5} \right)^2 = 3,840 \text{ psi}$$

$$\sigma_r = +6,720$$

$$\sigma_\theta = +6,720 - 3,840 = +2,880 \text{ psi}$$

$$\bar{\epsilon} = \frac{\sigma_\theta}{\sigma_r} = \frac{2,880}{6,720} = .429$$

$\therefore$ we have proved that the edge conditions are essentially the same as a clamped

edge (Note that for clamped edge $\bar{\epsilon} = -\nu^*$)

Average Stress Intensity Across Ligament due to Pressure

$$\sigma_{eff} = K \frac{R}{h} |\sigma_1| = 1.02 \left(\frac{1}{.25} \right) |6,720| = 27,500 \text{ psi}$$

$$\& 27,500 + 13,920 = 41,420$$

Combined Pressure & Thermal.

Peak Stresses in Perforated plates

① Peak stresses in the perforated portion

$$\sigma_{max} = Y \sigma_1 + P$$

$$Y = 6.7 \text{ @ } \frac{h}{B} = .25 \text{ From Fig 12}$$

P = Pressure acting on the surface

Full load to no load cycle

$$\sigma_1 = 6,720$$

$$\begin{aligned} \sigma_{max} &= 6.7(6,720) + 756 \\ &= 45,756 \end{aligned}$$

Start up cycle

$$\sigma_1 = 8,600$$

$$\begin{aligned} \sigma_{max} &= 6.7(8,600) + 756 \\ &= 61,200 \end{aligned}$$

② Peak stresses in Perforation adjacent to rim

$$\sigma_{max} = K_r \sigma_{rim} + P$$

$$K_r = \text{Value from Fig 13 @ } \left(\frac{D}{B} = .115\right) = 2.6$$

$$\sigma_{rim} = \sigma_1 = (\text{Nominal circum stress in rim})$$

$$P = \text{Pressure} \quad \& \quad \text{OTL} = 31\frac{1}{4}'' \text{ Dia. } \& \quad \text{Mean Plate Dia.} = 37\frac{3}{4}''$$

$$b = \frac{37\frac{3}{4} - 31\frac{1}{4}}{2} = 3\frac{1}{4} \quad \& \quad \frac{D}{B} = \frac{137.5}{3.25} = .115 \& \quad K_r = 2.6$$

Full load to no load cycle

$$\sigma_{rim} = \sigma_1 = 6,720$$

$$\sigma_{max} = 2.6(6,720) + 756 = 18,200$$

Start up cycle

$$\sigma_{rim} = \sigma_1 = 8,600$$

$$\sigma_{max} = 2.6(8,600) + 756 = 23,400$$

BY _____ DATE _____

SUBJECT _____

SHEET NO. 10 OF _____

CHKD. BY _____ DATE _____

JOB NO. _____

Thermal Stress

① thermal "Skin Effect" (1/8" S.S. clad)

$$\sigma_{max} = \frac{E \alpha T (T_p - T_s')}{(1 - \nu)}$$

$$T_s' = 389^\circ F = \text{skin temp}$$

$$T_p = 440 = \text{Primary temp}$$

$$\sigma_{max} = \frac{(27.2 \times 10^6)(6.9 \times 10^{-6})(440 - 390)}{(1 - .3)}$$

$$\sigma_{max} = \frac{(27.2)(6.9)(52)}{.7} = 13,920$$

From Navy Code For
Carbon Steel 212BUsing Temp = T_p

$$E = 27.2 \times 10^6$$

$$\alpha = 6.9 \times 10^{-6} \text{ diametral lane}$$

BY _____ DATE _____

SUBJECT _____

SHEET NO. 11 OF _____

CHKD. BY _____ DATE _____

JOB NO. _____

STRESSES FOR TEMP. DROP ACROSS DIAMETRAL LANE

$$\sigma_{max} = \frac{K_u E \alpha_T (T_H - T_C)}{2}$$

Where:

$$K_u = 9.75 \text{ From Fig 12 @ } R = 0$$

$$E = 5.16 \times 10^6$$

$$\sigma_{max} = \frac{9.75 (5.16 \times 10^6) (6. \times 10^{-6}) (448 - 428)}{2} = 3,470 \text{ psi}$$

STRESSES AT EDGES OF HOLES ADJACENT TO UNPERFORATED DIAMETRAL LANE

$$\sigma_{max} = \frac{K_D E \alpha_T (T_H - T_C)}{2(1-\nu)}$$

$$\sigma_{max} = \frac{1.63 (27.2) (6.9) (20)}{2(1.7)}$$

$$= 4,370$$

Where $K_D = 1.63$
From Fig 14

$$@ \frac{P}{D} = \frac{.37}{2.375} = .158$$

BY _____ DATE _____

SUBJECT SM-1SHEET NO. 12 OF _____

CHKD. BY _____ DATE _____

JOB NO. _____

Start up CyclePressure primary system = 1200 $\pm$ Temp. (450 $\leftrightarrow$ 431)Pressure secondary system = 200 $\pm$ temp (407)

From eq. 46 pag 1

$$\theta_s = \frac{1.285 P_s}{E_s} \left(\frac{q'}{t_s} \right)^{3/2} = \frac{1.285(200)}{29.2 \times 10^3} \left(\frac{22,812.5}{.8125} \right)^{1.5} = 1420 \times 10^{-6}$$

$$\begin{aligned} \# C_1^* &= \frac{2(K_n \theta_n - K_s \theta_s)}{D^*(1+\nu^*) + Q(K_s + K_n)} - \frac{q, q'}{\sqrt{8} D^* \left[D^*(1+\nu^*) + Q(K_s + K_n) \right]} \\ &= \frac{2[65.7 \times 10^{-6} - .8(1420) \times 10^{-6}]}{87.4 \times 10^6 [1.425] + 18.875(65.7 \times 10^6 + .8 \times 10^6)} - 508 \times 10^{-6} (1.1264) \\ &= 58.4 \times 10^{-6} - 572 \times 10^{-6} = -513.6 \times 10^{-6} \end{aligned}$$

$$\begin{aligned} M_r &= \frac{(3+\nu^*)}{16} q r^2 + D(1+\nu^*) \frac{C_1}{2} \\ &= \frac{(3.425) \times 10^3 (18.875)^2}{16} - \frac{87.4 \times 10^6 (1.425) (-513.6 \times 10^{-6})}{2} \\ &= 76.3 \times 10^3 - 32.9 \times 10^3 = 43.4 \times 10^3 \end{aligned}$$

$$\sigma_{max} = \frac{6(43.4 \times 10^3)}{(5.5)^2} = 8,600 \text{ psi @ Tube sheet edge}$$

BY _____ DATE _____

SUBJECT _____

SHEET NO. 13 OF _____

CHKD. BY _____ DATE _____

JOB NO. _____

Average stress intensity across ligament
due to pressure

$$\sigma_{eff} = K \frac{P}{h} |\sigma_i| = 1.02 \left(\frac{1}{.25} \right) |8,600| = 35,300$$

Combined Press & Thermal

$$35,300 + 13,920 = 49,200$$

Pea

BY JTB DATE 1/23/62
 CHKD. BY _____ DATE _____

ALCO PRODUCTS INC.
 SUBJECT SM-1 Steam Generator
Tube Sheet - Stress Analysis

SHEET NO. 14 OF _____
 JOB NO. _____

Operating conditions during primary system hydrostatic testing

Primary $P = 2250$ psig
 $T = 680^\circ F$

Secondary $P = 0$ psig
 $T = 680^\circ F$

FROM NAVY CODE

$$E_s = 29.6 \times 10^6 \text{ #/in}^2$$

$$E_h = 29.6 \times 10^6 \text{ #/in}^2$$

$$\alpha_s = 6.1 \times 10^{-6} \text{ 1/in}^\circ F$$

$$\alpha_h = 6.1 \times 10^{-6} \text{ 1/in}^\circ F$$

$$\textcircled{1} \sigma_{max} = \frac{6 M_r}{h^2 \eta}$$

$$\textcircled{2} M_r = \frac{(3+\nu)}{16} q r^2 + \frac{D(1+\nu)C_1}{2}$$

$$\textcircled{3} D = \frac{E h^3 \eta w}{12(1-\nu^2)}$$

$$\textcircled{4} C_1 = \frac{2(K_h \theta_h - K_s \theta_s)}{D(1+\nu) + a(K_s + K_h + K_e)} - \frac{q a^2 [D(3+\nu) + a(K_s + K_h + K_e)]}{8 D [D(1+\nu) + a(K_s + K_h + K_e)]}$$

$$\textcircled{5} \eta w = .5 \left(1 - .952 \frac{d}{P} \right)$$

$$\textcircled{6} \theta_s = \frac{3^{1/4} (1 - \nu_s^2)^{1/4} P_s}{E_s} \left(\frac{a'}{t_s} \right)^{3/2} = \frac{1.285 P_s}{E_s} \left(\frac{a'}{t_s} \right)^{3/2}$$

nomenclature

r = radial coordinate

E = Mod. of elast.

h = tube sheet thickness

ηw = Deflection η

q = uniform pressure

a = Plate radius

a' = Shell radius

D = Flexural rigidity

K = Rotation stiffness

θ = Edge rotation

d = Outside tube dia.

P = Tube Pitch.

This method of analysis is from Journal of applied mechanics sept 1956, "Rational Analysis of heat exchanger tube sheet stresses" by Yi-Yuan Yu.

$$\textcircled{7} \quad \Theta_n = \frac{3^{1/4} (1 - \nu_n^2)^{1/4} P_n \left(\frac{a'}{t_n} \right)^{3/2}}{E_n} = \frac{1.285 P_n \left(\frac{a'}{t_n} \right)^{3/2}}{E_n}$$

$$\textcircled{8} \quad K_n = \frac{E_n t_n^{5/2}}{2 \times 3^{3/4} (1 - \nu_n^2)^{3/4} a'^{1/2}} = \frac{E_n t_n^{5/2}}{4.25 a'^{1/2}}$$

$$\textcircled{9} \quad K_s = \frac{E_s t_s^{5/2}}{2 \times 3^{3/4} (1 - \nu_s^2)^{3/4} a'^{1/2}} = \frac{E_s t_s^{5/2}}{4.25 a'^{1/2}}$$

From Fig

$$a' = 22.8125$$

$$h = 5.5''$$

$$t_n = 4.75$$

$$t_s = .8125$$

$$d = 3/4''$$

$$P = 1''$$

$$\nu = .3$$

$$\text{Eq. } \textcircled{5} \quad \eta_w = .5 \left(1 - .952 \frac{d}{P} \right) = .5 \left[1 - .952 \left(\frac{.75}{1} \right) \right] = .143$$

$$\textcircled{3} \quad D = \frac{E h^3 \eta_w}{12 (1 - \nu^2)} = \frac{29.6 \times 10^6 \text{ psi} (5.5)^3 (.143)}{12 (1 - .09)} = 64.4 \times 10^6 \text{ lb/in}$$

$$\textcircled{8} \quad K_n = \frac{E_n t_n^{5/2}}{4.25 a'^{1/2}} = \frac{29.6 \times 10^6 (4.75)^{2.5}}{4.25 (22.8125)^{.5}} = 71.5 \times 10^6$$

$$\textcircled{9} \quad K_s = \frac{E_s t_s^{5/2}}{4.25 a'^{1/2}} = \frac{29.6 \times 10^6 (.8125)^{2.5}}{4.25 (22.8125)^{.5}} = .870 \times 10^6$$

$$\textcircled{6} \quad \Theta_s = \frac{1.285 P_s \left(\frac{a'}{t_s} \right)^{3/2}}{E_s} = \frac{1.285 (15) (22.8125)^{3/2}}{29.6 \times 10^6 (.8125)} = 97.7 \times 10^{-6}$$

$$\textcircled{7} \quad \Theta_h = \frac{1.285 (2250)}{29.6 \times 10^6} \left[\frac{22.8125}{4.75} \right]^{1.5} = 1035 \times 10^{-6}$$

$$\textcircled{4} \quad C_1 = \frac{2(K_n \Theta_h - K_s \Theta_s)}{D(1-\nu) + a(K_s + K_n + K_f)} - \frac{qa^2}{8D} \left[\frac{D(3+\nu) + a(K_s + K_n + K_f)}{D(1+\nu) + a(K_s + K_n + K_f)} \right]$$

$$\begin{aligned} (A) &= \frac{2(71.5 \times 10^6 \cdot 1035 \times 10^{-6} - 18.875 \times 10^6 \cdot 97.7 \times 10^{-6})}{64.4 \times 10^6 (1-0.3) + 18.875 (18.87 \times 10^6 + 71.5 \times 10^6)} = (A) \\ &= \frac{73,915(2)}{45,001,364} = 1.022 \times 10^{-4} \end{aligned}$$

$$\begin{aligned} (B) &= -\frac{2235(18.875)^2}{8(64.4 \times 10^6)} \left[\frac{64.4 \times 10^6 (3.3) + 18.875 (72.3)}{64.4 \times 10^6 (1.3) + 1364 \times 10^6} \right] \\ &= 1.546 \times 10^{-3} \left[\frac{1576 \times 10^6}{1447 \times 10^6} \right] = -1.685 \times 10^{-3} \end{aligned}$$

$$\therefore C_1 = 1.022 \times 10^{-4} - 1.685 \times 10^{-3} = -15.83 \times 10^{-4}$$

At Tube sheet center ($r=0$)

$$\begin{aligned} \textcircled{2} \quad M_r &= \frac{(3+\nu)}{16} q \left[r^2 + D(1+\nu) \frac{C_1}{2} \right] = -64.4 \times 10^6 (1.3) \frac{(-15.83 \times 10^{-4})}{2} \\ &= -66 \times 10^3 \end{aligned}$$

At tube sheet edge $r=a=18.875$

$$M_r = \frac{(3.3)}{16} (2235) (356) + (-66 \times 10^3) = 98 \times 10^3$$

ALCO PRODUCTS INC.

BY _____ DATE _____

SUBJECT _____

SHEET NO. 17 OF _____

CHKD. BY _____ DATE _____

JOB NO. _____

$$\textcircled{1} \quad \sigma_{\max} = \frac{6Mr}{h^2} \eta$$

Gardner (Triangular Pitch)

$$\eta = 1 - \frac{3}{\pi} \sin^{-1} \left(\frac{\sqrt{2}}{2} \cdot \frac{d}{P} \right) = 1 - \frac{3}{\pi} \sin^{-1} \left(\frac{\sqrt{2}}{2} \cdot \frac{.75}{1} \right)$$

$$= 1 - \frac{3}{\pi} \sin^{-1}(32^\circ) = 1 - \left(\frac{32\pi}{180} \right) = 1 - \frac{32}{60} = .467$$

Miller (Triangular Pitch)

$$\eta = 1 - \frac{\pi}{6} \sqrt{3} \frac{d^2}{P^2} = 1 - \pi \left(\frac{1.73}{6} \right) \cdot \frac{(.563)}{1} = 1 - .51 = .49$$

$$\sigma_{\max} = \frac{6(98 \times 10^3)}{(5.5)^2 (.467)} = 41,600 \text{ psi @ edge } \sim \text{Gardner}$$

$$\sigma_{\max} = \frac{6(98 \times 10^3)}{5.5^2 (.49)} = 39,700 \text{ @ Edge } \sim \text{Miller}$$

BY _____ DATE _____

SUBJECT _____

SHEET NO. 18 OF _____

CHKD. BY _____ DATE _____

JOB NO. _____

Design of Perforated Plate's

by W.T. O'Donnell > Paper No 61-WA-115
B.F. Langer JAN. 1962

Atco drawing H-152400
tube OD = .75

$$\frac{h}{r} = \frac{.25}{1.00} = .25$$

$$E^* @ \frac{h}{r} = .25$$

$$\frac{E^*}{E} = .191, \nu^* = .425, \frac{D^*}{D} = .21$$

$$E^* = .191 (29.6 \times 10^6) = 5.66 \times 10^6$$

$$D^* = \frac{E^* H^3}{12(1-\nu^{*2})} = \frac{5.66 \times 10^6 (5.3)^3}{12 (1-.181)} = 95.8 \times 10^6$$

$$C^* = \frac{Z (K_h \Theta_h - K_s \Theta_s)}{D^* (1+\nu^*) + a (K_s + K_h + K_f)} - \frac{q a^2}{8 D^*} \left[\frac{D^* (3+\nu^*) + a [K_s + K_h]}{D^* (1+\nu^*) + a [K_s + K_h]} \right]$$

$$= \frac{2 (73,915)}{95.8 (1-.425) + 1.364 \times 10^6} - \frac{2235 (356)}{8 (95.8 \times 10^6)} \left[\frac{95.8 \times 10^6 (3.3) + 1364 \times 10^6}{95.8 \times 10^6 (1.21) + 1364 \times 10^6} \right]$$

$$= .984 \times 10^{-4} - 11.73 \times 10^{-4} = 10.74 \times 10^{-4}$$

$$M_r = \frac{(3+\nu^*) q r^2 + D^* (1+\nu^*) C_1^*}{16}$$

$$M_r = \frac{(3+4.25)(2235)(356) + 93.8 \times 10^6 (1+4.25)(-10.71 \times 10^{-9})}{16}$$

$$= 17.1 \times 10^4 - 7.3 \times 10^4 = 9.69 \times 10^4$$

$$@ r=a \quad M_r = 9.69 \times 10^4$$

$$@ r=0 \quad M_r = -7.31 \times 10^4$$

$$\therefore \sigma_{max} = \frac{6 M_r}{h^2} = \frac{6 (9.69 \times 10^3)}{30.3} = 19.20 \times 10^3$$

$$\therefore \sigma_{max} = \sigma_r = 19,200$$

LIGAMENT STRESS

INTENSITIES

biaxiality ratio $\beta = \frac{\sigma_r}{\sigma_\theta}$ or $\frac{\sigma_\theta}{\sigma_r}$ whichever gives $-1 \leq \beta \leq 1$

$$\beta \begin{cases} = 1, & \text{For Isotropic loads} \\ = 0, & \text{For uniaxial loads} \\ = -1, & \text{For pure shear} \end{cases}$$

$$\sigma_{eff} = K \frac{R}{h} |\sigma_1|$$

Fig. 10

where: σ_{eff} = ligament stress intensity based on stresses averaged across minimum ligament section at either plate surface

K = value from Fig. 10.

$\frac{R}{h}$ = reciprocal of ligament eff. Fig. 6

$\sigma_1 = \sigma_\theta$ or σ_r whichever has the greatest absolute value.

"For Example" $\sigma_r = -3000$, $\sigma_\theta = 2500$
 $\sigma_1 = -3000 \text{ psi}$ & $|\sigma_1| = 3000 \text{ psi}$

σ_r & σ_θ : stresses at either surface of equiv. solid plate

BY _____ DATE _____

SUBJECT _____

SHEET NO. 20 OF _____

CHKD. BY _____ DATE _____

JOB NO. _____

From Calc. $\sim \tau_{max} = \frac{6 M_r}{h^2} = 19,200$

From "Theory of Shells & Plate" Timoshenko

$$M_r = \frac{8}{16} [a^2(1+\nu) - r^2(3+\nu)] \quad @ \quad r=a$$

$$= \frac{2235}{16} [a^2(-2)] = \frac{-2235}{8} (18.875)^2 = -99,500$$

$$\therefore \tau_r = \frac{6 M_r}{h^2} = \frac{6(-99,500)}{(5.5)^2} = -19,700$$

$$\tau_\theta = \tau_r + (1-\nu^*) \tau_{calc.} = 19,200 + (1-.425)(-19,700)$$

(Page 6)

$$= 19,200 - 11,300 = 7,900$$

$$\therefore \beta = \frac{\tau_\theta}{\tau_r} = \frac{7,900}{19,200} = .413$$

$$\frac{.012}{.425} \approx 2.8\%$$

therefore clamped edge
assumption good

From Fig 10 $K = 1.025$

$$\pm \sigma_{eff} = K \frac{R}{h} |\tau_1| = 1.025 \frac{1}{(.25)} |19,200| = 79,000$$

BY _____ DATE _____

SUBJECT _____

SHEET NO. 21 OF _____

CHKD. BY _____ DATE _____

JOB NO. _____

Peak Stresses in Perforated Plates

MAXIMUM STRESS FOR
ANY PARTICULAR THERMAL
OR PRESSURE LOAD

$$\sigma_{max} = \gamma \sigma_1 + P$$

Eq. 10

$$= 7(19,200) + 2250$$

$\sigma_1 = \sigma_r \text{ or } \sigma_\theta$ (whichever has
largest absolute value)

$$= 136,450$$

γ @ given in Fig 12 @ $\frac{h}{R} = .25$

$$= 7$$

P = pressure acting on surface

Local Stresses at the perforations adjacent to rim

$$\sigma_{max} = K_r \sigma_{rim} + P$$

σ_{rim} = NOMINAL bending
plus Membrane stress
at inside OF rim

$$K_r \text{ FROM FIG 13 @ } \left[\frac{c}{b} = \frac{3/8}{13/4} = \frac{3}{26} = .115 \right]$$

$$\therefore K_r = 2.6$$

$$OTL = 31\frac{1}{4} \text{ Dia}$$

$$\text{Mean plate dia} = 37\frac{3}{4}$$

$$b = \frac{37.75 - 31.25}{2}$$

$$= 3.25$$

$$\sigma_{max} = 2.6(19,200) + 2250 = 52,250$$

BY _____ DATE _____

SUBJECT _____

SHEET NO. 22 OF _____

CHKD. BY _____ DATE _____

JOB NO. _____

THERMALLY INDUCED STRESSES

Thermal skin effect

$$\sigma_{\max} = E \alpha_r (T_p - T_s') / (1 - \nu)$$

[Eq. 12]

 α_r = thermal expansion coefficient
in/in/deg F

during Hydro primary temp
= Secondary tubesheet
surface temp.

 T_p = primary temp, deg F (68)

T_s' = metal temperature at
secondary tubesheet
surface, deg F (68)

∴ No thermal stress.

Stresses For Temperature drop Across diametral lane
of U-tube type Steam Generator Tubesheet

$$\sigma_{\max} = \frac{K_u E^* \alpha (T_H - T_C)}{2} \approx 0$$

[Eq. 13]

K_u = uniaxial ($\epsilon = 0$) stress Multiplier
From Fig. 12

 $K_u = 9.7$

E^* = effective elastic modulus
= 5.6×10^6

Stresses at the Edge of the holes adjacent to the
unperforated diametral lane

$$\sigma_{\max} = \frac{K_d E \alpha_r (T_H - T_C)}{2(1 - \nu)}$$

[Eq. 14]

K_d = stress concentration factor
From Fig. 14 $\frac{C}{D} = .158$

 $K_d = 1.66$ $C = 3/4"$ $\epsilon = 3/8$ $D = 2 3/8$ $\sigma_{\max} = 0$

$d = .75"$
 $P = 1"$
 $\nu = .3$
 $a' = 22.8125$
 $h = 5.5$

Eq #5

$$\eta_w = .5(1 - .952 \frac{P}{d}) = .5 \left[1 - .952 \left(\frac{1}{.75} \right) \right] = .143$$

Eq #3

$$D = \frac{E h^3 \eta_w}{12(1 - \nu^2)} = \frac{29.6 \times 10^6 \text{ psi/in}^2 (5.5)^3 (.143)}{12(1 - .09)} = 64.4 \times 10^6 \text{ lb/in}$$

Eq #8

$$K_h = \frac{E_n (t_h)^{5/2}}{4.25 a'^{1/2}} = \frac{29.6 \times 10^6 (4.75)^{2.5}}{4.25 (22.8125)^{1/2}} = 71.5 \times 10^6$$

9

$$K_s = \frac{E_s t_s^{5/2}}{4.25 a'^{1/2}} = \frac{29.6 \times 10^6 (.8125)^{2.5}}{4.25 (22.8125)^{1/2}} = .870 \times 10^6$$

BY _____ DATE _____

SUBJECT _____

SHEET NO. 24 OF _____

CHKD. BY _____ DATE _____

JOB NO. _____

$$h_{air} = .38 (\Delta T)^{.25} = .38 (150 - 100)^{.25}$$

$$h_{air} = 1.01$$

$$\text{IFT Strip } 46.375'' \text{ Dia}$$

$$q_{air} = h A \Delta T \quad \& \quad \frac{1' \times \pi D}{12} = \frac{3.14 (46.375)}{12} = 12.1 \text{ FT}^2$$

$$\therefore \dot{Q}_{air} = 12.1 (1.01) (50) = 613 \frac{\text{Btu}}{\text{hr per FT length}}$$

$$q_{in} = \frac{K A \Delta T}{\Delta x} = \frac{324 (12.1) (440 - T)}{4.75}$$

$$q_{out} = \frac{.4 (12.1) (T - 150)}{2} \quad \& \quad q_{in} = q_{out}$$

$$\frac{.4 (12.1) (T - 150)}{2} = \frac{324 (12.1) (440 - T)}{4.75}$$

$$\& \quad T \approx 440^\circ$$

BY JJB DATE 3/15/62 SUBJECT Shock ON
SM-1 Tube Sheet
during loss of load

SHEET NO. 25 OF
 JOB NO.

FROM HEAT TRANSFER NOTES

$$h = 1.6 T_F^{.7} \left(\frac{\Delta T}{D} \right)^{.25}$$

$$= 1.6 (429)^{.7} \left(\frac{50(12)}{37.75} \right)^{.25}$$

$$= 1.6 (70) (1.12) = 125.5 \frac{\text{Btu}}{\text{ft}^2 \text{hr } ^\circ\text{F}}$$

From NAVY code

$$\frac{12K}{hr} = \frac{12 (25.3) \frac{\text{Btu}}{\text{ft}^2 \text{hr } ^\circ\text{F}}}{(125.5) \frac{\text{Btu}}{\text{ft}^2 \text{hr } ^\circ\text{F}} (5.5) \text{in}} = .442$$

$$\phi \lambda = \frac{\epsilon \theta}{t^2} = \frac{.018 \text{in}^2 \times 3000}{(5.5)^2 \times 30.2} = .00179$$

From NAVY Code

$$\eta_i \approx .40 \quad \phi \eta_o \approx .06$$

@ $\lambda = .00179$
 @ $\frac{12K}{hr} = .442$

$$\therefore \sigma = \frac{E \alpha (\Delta T_c)}{1 - \nu} \eta = \frac{210 (500)}{.7} \eta = 1500 \eta$$

$$\phi @ \eta_i = .4 \quad \sigma = 1500 (.4) = 6,000 \text{ psi}$$

As shown above the stress imposed is small

As a result of a thermal shock when the plant goes

From no load to full load in 3 seconds

loss of load in 3 sec

NOTE

{ During loss of load
 you unstress the
 tube sheet, therefore
 gain of load in 3 sec's
 will be considered

$$T_F = \frac{450 - 407}{2} = 257 = 429$$

NAVY Co =

$$K = 25.3 \frac{\text{Btu}}{\text{hr } ^\circ\text{F}}$$

$$\epsilon_{\text{thermal}} = .018 \frac{\text{in}^2}{\text{sec}}$$

DIFFUSIVITY

$$\text{Inst. } E \alpha = 210 \frac{\text{psi}}{^\circ\text{F}}$$

@ 429

BY _____ DATE _____

SUBJECT _____

SHEET NO. 26 OF _____

CHKD. BY _____ DATE _____

JOB NO. _____

IN the Fatigue Analysis, this stress was considered in the loss of load cycle & is the result of a thermal skin effect. The equation is the same as that used on previous page except the $\eta = 1$.

IN conclusion the "loss of load cycle" does not create a thermal shock of severe magnitude nor does it limit the plant by limiting the number of cycles.