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LMFBR DEMONSTRATION PLANT
STEAM GENERATOR

SUPERHEATER DUPLEX TUBE STEADY-STATE
ANALYSIS DEMONSTRATING $2\frac{1}{4}\text{Cr}-1\text{Mo}$ AS AN
ACCEPTABLE REFERENCE MATERIAL

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By
R. L. Flury

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Approved:

A. Lohmeier, Project Manager
LMFBR Components Development

Approved:

J. M. Duke, Manager
Analytic Methods Development

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Westinghouse Electric Corporation
Tampa Division
P.O. Box 19218
Tampa, Florida 33616

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ABSTRACT

Preliminary analysis of the proposed super-heater duplex tube ($2\frac{1}{4}\text{Cr-1Mo}$) has been performed for the steady state condition. All locations evaluated were found to satisfy the criteria set forth in Code Case 1331-8 Section 4.3 and 5.2b.

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1.0 INTRODUCTION

Thermal expansion accommodation is a problem associated with all tube-shell superheater designs. The presence of a duplex tube and low allowable stress levels consistent with high temperature superheater operation simply aggravates this condition. The intent of this analysis is to evaluate the use of 2-1/4 Cr-1 Mo as the reference superheater duplex tube material.

The analysis attacks (1) tube-to-tube-to-shell interaction, (2) classic thick-walled cylinder analysis of pressure and thermal stress components (with resultant radial interaction and/or gap opening), and (3) bending due to differential tubesheet radial expansion. Analytic scope is limited to the superheater steady state condition. Justification for this limitation (for preliminary evaluation only) is recognized upon review of References 2 and 3.

The resultant stress intensities are evaluated in accordance with Code Case 1331-8, Nuclear Components in Elevated Temperature Service.

2.0 SUMMARY

Preliminary analysis of the proposed superheater duplex tube (2-1/4 Cr-1 Mo) has been performed for steady state condition. Areas deemed critical to design feasibility were evaluated in accordance with Code Case 1331-8.

A summary of the findings are shown in Tables 2-1 through 2-4. Note that in all cases and locations the tube meets the referenced criteria, i.e.,

2-1/4 Cr-1 Mo is an acceptable superheater tube material.

TABLE 2-1

INNER TUBE LIMIT RATIO AXIAL CONSTRAINT - FREE

Node*	P_M/S_{MT}	$P_L + P_B/KS_T$	$P_L + \frac{P_B}{K} + Q_R/S_q$	
			Inside Dia.	Outside Dia.
2	0.5	0.35	0.54	0.53
4	0.5	0.35	0.59	0.1
26	0.63	0.90	0.69	0.35
86	0.56	0.89	0.64	0.35
110	0.68	0.63	0.48	0.26
126	0.81	0.77	0.48	0.37
128	0.71	0.66	0.46	0.31

* Reference Figure 4-2 for node locations.

TABLE 2-2

INNER TUBE LIMIT RATIO AXIAL CONSTRAINT - BONDED

Node	P_M/S_{MT}	$P_L + P_B/KS_T$	$P_L + \frac{P_B}{K} + Q_R/S_q$	
			Inside Dia.	Outside Dia.
2	0.79	0.55	0.78	0.73
4	0.68	0.47	0.71	0.22
26	0.72	0.68	0.60	0.23
86	0.65	0.61	0.53	0.21
110	0.59	0.55	0.43	0.22
126	0.49	0.47	0.32	0.20
128	0.70	0.65	0.46	0.35

TABLE 2-3

OUTER TUBE LIMIT RATIO AXIAL CONSTRAINT - FREE

Node	P_M/S_{MT}	$P_L + P_B/KS_T$	$P_L + \frac{P_B}{K} + Q_R/S_q$	
			Inside Dia.	Outside Dia.
204	0.26	0.22	0.30	0.33
226	0.33	0.49	0.28	0.45
286	0.21	0.43	0.24	0.37
310	0.33	0.28	0.21	0.18
326	0.61	0.56	0.34	0.30

TABLE 2-4

OUTER TUBE LIMIT RATIO AXIAL CONSTRAINT - BONDED

Node	P_M/S_{MT}	$P_L + P_B/KS_T$	$P_L + \frac{P_B}{K} + Q_R/S_q$	
			Inside Dia.	Outside Dia.
204	0.41	0.34	0.29	0.41
226	0.41	0.36	0.26	0.39
286	0.31	0.26	0.23	0.29
310	0.27	0.23	0.21	0.15
326	0.46	0.42	0.33	0.19

3.0 THERMAL DATA

Axial tube temperature distributions (mean wall temperature) for the superheater steady state condition are presented in Reference 1. The required reworking* of this data for the minimum tube length (minimum bend radius) is presented in Figure 3-1.

Tube surface temperatures⁽¹⁾ employed in Section 4.2 are presented below.

TUBE SURFACE TEMPERATURES

T_1 - Inner Tube I.D.

T_4 - Outer Tube O.D.

Node Location	T_1	Node Location	T_4
2	613 [✓]		
4	722	204	842
26	801	226	882
86	839	286	898
110	897	310	923
129	923	326	934
128	909 [✓]		

✓ - isothermal

* Reworking represents an adjustment in the percent location of the U-bend region, i.e., node 26 shifts from 26 to 31 percent for the shorter tube length.

Figure 3-1 Fluid and Average Inner and Outer Wall Temperatures Vs. Percent Tube Length

4.0 DUPLEX TUBE STRUCTURAL EVALUATION

Structural evaluation attacks (1) tube-to-tube-to-shell interaction* and (2) classic thick-walled cylinder analysis of pressure and thermal stress components. The condition evaluated is limited to the superheater steady state.

4.1 Tube-to-Tube-to-Shell Interaction Analysis

4.1.1 Model Development

Schematic representation of the tube-shell geometry may be seen in Figure 4-1. Structural idealization of this geometry is accomplished via finite element representation. Node locations of prime interest are shown in Figure 4-2. Note that the model uses one duplex tube. Flexibility of the sodium-steam tubesheet connector section is modified accordingly, i.e.,

$$Flex_{\text{model connector}} = N_{\text{number tubes}} Flex_{\text{connector}}$$

The above modification insures consistency in the desired deformation solution.

The imposed boundary displacement and/or displacement coupling constraints are as follows:

Shell support structure boundary displacement and displacement coupling constraints;

Support structure nodes 456, 531, 532, 533

Pertinent shell nodes 402, 510

A. Boundary displacement constraints,

$$UX_{456} = 0$$

$$UX_{531} = UY_{531} = 0$$

* Thermally induced axial interaction, tube-to-tube radial interaction or interference is the subject of Section 4.2.

Figure 4-1 Schematic Representation of the Tube-Shell Geometry

Inner Tube Node Sequence	1 thru 129
Inter Tube Node Sequence	202 thru 328
Shell Node Sequence	401 thru 529
Support Structure Node	531, 532, 533

Figure 4-2 Node Locations of Prime Interest

B. Shell-to-shell support structure displacement coupling constraints,

$$UX_{402} = UX_{532}$$

$$UY_{402} = UY_{532}$$

$$UX_{510} = UX_{533}$$

$$UY_{510} = UY_{533}$$

Tube_{inner} - to - tube_{outer} - to-shell

Displacement coupling constraints;

Inner tube node sequence 1 thru 129

Outer tube node sequence 202 thru 328

Pertinent shell nodes 401, 402, 421, 528, 529

A. Tube-to-tube displacement coupling constraints (axially free)

Tube -to-tube displacement coupling can best be understood by observing Figure 4-3. The figure is a graphic representation of:

$$UX_N = UX_{N+200}$$

$$\emptyset Z_N = \emptyset Z_{N+200}$$

The equivalent statement for the U-bend region, defined in cylindrical coordinates, is simply

$$UR_N = UR_{N+200}$$

$$\emptyset Z_N = \emptyset Z_{N+200}$$

B. Tube-to-tube displacement coupling constraint (axial bonding)

Evaluation for axial bonding may be modeled by adding the following constraint to that indicated above.

$$UY_N = UY_{N+200}$$

$$U\emptyset_Z = U\emptyset_{N+200}$$

Figure 4-3 Graphic Representation of the
Imposed Tube_{Inner} - To - Tube_{Outer} Coupling Constraint

Note: The condition of axial bonding does not represent a single wall tube,

$t = t_{\text{inner}} + t_{\text{outer}}$, rather the coupling demonstrates discrete or intermittent locations of axial bonding. Model definition is sufficiently fine such that the maximum stress is captured.

C. Tube-to-shell displacement coupling constraint

$$UX_1 = UX_{401}$$

$$UY_1 = UY_{401}$$

$$\emptyset Z_1 = \emptyset Z_{401}$$

$$UX_2 = UX_{202} = UX_{402}$$

$$\emptyset Z_2 = \emptyset Z_{202} = \emptyset Z_{402}$$

$$UX_{128} = UX_{328} = UX_{528}$$

$$\emptyset Z_{128} = \emptyset Z_{328} = \emptyset Z_{528}$$

$$UX_{129} = UX_{529}$$

$$UY_{129} = UY_{529}$$

$$\emptyset Z_{129} = \emptyset Z_{529}$$

Tube wall thickness and diameter used in the analysis represent end-of-life conditions, i.e.,

	Inner Tube	Outer Tube
Outside Diameter	0.715 in	0.062 in
Wall Thickness	0.871	0.078

4.1.2 Material Properties (Elastic)

Material properties used in the analysis are as follows:

Tube Material - 2-1/4 Cr-1 Mo

Temperature	Elastic Modulus $E \times 10^{-6}$	Thermal Expansion $\alpha \times 10^6$ $\frac{\text{in}}{\text{in-}^\circ\text{F}}$	Poisson's Ratio
400°F	28.5 psi	7.06	0.29
500	27.9	7.22	0.297
600	27.3	7.37	0.3
700	26.6	7.51	0.305
800	25.8	7.63	0.304
900	24.6	7.73	0.301
950	23.8	7.77	0.3

4.1.3 Stress Analysis

Tube-to-tube-to-shell interaction evaluation is conducted for the superheater steady state condition, i.e.,

Thermal Load - Average tube temperatures shown in Figure 3-1.

Equivalent* Pressure Load, ΔP - Inner Tube, 1245 psi
Outer Tube, 89.5 psi

* Pressure loads represent an equivalent force system, i.e.,

$$\left(\Delta P_{\text{inner tube}} \right)_{\text{equ.}} = P_{\text{steam}} - \frac{D^2}{d^2} P_{\text{helium}}$$

Note that as the ratio $\frac{D}{d}$ approaches 1.0 (thin wall theory)

$$\left(\Delta P_{\text{inner tube}} \right)_{\text{equ.}} = P_{\text{steam}} - P_{\text{helium}}$$

The above assumes

$$P_{\text{steam}} = \left(\frac{P_{\text{inlet}} + P_{\text{outlet}}}{2} \right)_{\text{steam}}$$

The above loads, when applied to the analytic model previously presented, result in the displacements shown in Figure 4-4 (Axial Constraint - Free). Similar displacements (not shown) result for the bonded axial constraint condition, i.e.,

	<u>Free</u>	<u>Bonded</u>
UX ₅₆	0.153	0.148
UY ₅₆	-1.727	-1.729

Stresses associated with these deformed shapes are tabulated in Tables 4-1 through 4-2. Bending stress signatures, of importance in the U-bend region, are shown in Figures 4-5 and 4-6.

Lateral motion (displacement) of each tube within a given tubesheet is defined by the relation $R_{TS} \cdot \alpha \cdot T_{TS}$. Tubes common to both sodium and steam tubesheets (inner tube lengths in the helium plenum zone) experience differential end displacements of magnitude $R_{TS} \cdot \alpha \cdot \Delta T_{TS}$. The resultant secondary bending stress related to this displacement is defined by the relation -

$$Q_{\text{bending}} = 6E\alpha R_T R_{TS} \cdot \frac{\Delta T_{TS}}{L_T^2}$$

Figure 4-4 Superheater Steady State Displacement,
Axial Constraint-Free TFRF128

Figure 4-5 Inner and Outer Tube Bending Stress Resultants for the Superheater Steady State Condition, Combined Pressure Plus Thermal

Figure 4-6 Inner and Outer Tube Bending Stress Resultant for the Superheater Steady State Condition, Axial Constraint-Free

TABLE 4-1

INNER TUBE STRESS RESULTANTS
FOR THE SUPERHEATER STEADY STATE CONDITION

Axial Stress Component
Axial Constraint - Free (TFRF128)

Node	Primary Stress		Secondary Stress
	Memb.	Bending	Bending
2	8070 psi		5820 psi
4	8070		
26	8030	5070 psi	
86	5660	5550	
110	5610		
126	5610		
128	5610		260

Axial Stress Component
Axial Constraint - Bonded (TFRF196)

Node	Primary Stress		Secondary Stress
	Memb.	Bending	Bending
2*	13380 psi		5820 psi
4	11230		
26	9390	320 psi	
86	7130	310	
110	4830		
126	2940		
128*	5610		260

* TFRF128

TABLE 4-2

OUTER TUBE STRESS RESULTANTS
FOR THE SUPERHEATER STEADY STATE CONDITION

Axial Stress Component
Axial Constraint - Free (TFRF128)

Node	Primary Stress		Secondary Stress
	Memb.	Bending	Bending
204	-3340 psi		
226	-3310	2740 psi	
286	-1760	3000	
310	-1730		
326	-1730		

Axial Stress Component
Axial Constraint - Bonded (TFRF196)

Node	Primary Stress		Secondary Stress
	Memb.	Bending	Bending
204	-5400 psi		
226	-4200	100 psi	
286	-2720	55	
310	-1219		
326	20

Figure 4-7 Secondary Bending Stress
 Q_{Bending} Vs. Parameters ΔT and L

Using the known parameters for the current design, the above expression reduces to

$$Q_{\text{bending}} = 9323 \cdot \frac{\Delta T_{\text{TS}}}{L_T^2}$$

$$E = 27.3 \cdot 10^6 \text{ psi}$$

$$\alpha = 7.37 \cdot 10^{-6} \text{ in/in-}^\circ\text{F}$$

$$R_T = 0.3575 \text{ inch}$$

$$R_{\text{TS}} = 21.625 \text{ inch}$$

Resultant secondary bending stress is plotted against parameters ΔT_{TS} and L in Figure 4-7.

4.2 Thick-Walled Cylinder Analysis Establishing Pressure (Hoop) and Radial Thermal Gradient (Hoop and Axial) Stress Components

4.2.1 Equation Definition

The equations used within this portion of the analysis are presented below. The actual manner in which these equations are used has been adequately documented in earlier work by this author⁽²⁾ and others⁽³⁾; hence, no further documentation will be presented here.

Equation Definition (Thermal)

The assumption of quasistatic heat flow through the duplex tube allows writing of the following equations:

$$T_1 = \text{inner wall temperature}$$

$$T_2 = T_1 + K \cdot \frac{\ln(R_2/R_1)}{K_{12}}$$

$$T_3 = T_2 + K \cdot \frac{\Delta R_{23}}{R_2 K_{23}}$$

$$T_4 = \text{outer wall temperature}$$

$$K = \frac{T_4 - T_1}{\frac{\ln(R_2/R_1)}{K_{12}} + \frac{\Delta R_{23}}{R_2 K_{23}} + \frac{\ln(R_4/R_3)}{K_{34}}}$$

Solution for intermediate temperatures in each tube is obtained from the following :

$$T_R = T_1 - (T_1 - T_2) \frac{\ln(R/R_1)}{\ln(R_2/R_1)} \quad R_1 \leq R \leq R_2$$

$$T_R = T_3 - (T_3 - T_4) \frac{\ln(R/R_3)}{\ln(R_4/R_3)} \quad R_3 \leq R \leq R_4$$

Duplex tube inner and outer surface temperatures T_1 and T_4 are provided as boundary conditions from the thermal/hydraulic data presented in Section 3.2.

Equation Definition (Deformation)

Radial displacement for each wall of the duplex tube may be written as follows:

$$\Delta R = \frac{R^2(P_1 R_1^2 - P_2 R_2^2)(1-2\nu) + (P_1 - P_2)R_1^2 R_2^2(1+\nu)}{ER(R_2^2 - R_1^2)} + \frac{2\alpha R}{(R_2^2 - R_1^2)} \int_{R_1}^{R_2} T_R R \cdot dR$$

Carrying out the above integration for T_R in $R_1 \leq R \leq R_2$ yields

$$\begin{aligned} \frac{2\alpha R}{(R_2^2 - R_1^2)} \cdot \left[\frac{T_1(R_2^2 - R_1^2)}{2} + \frac{(T_1 - T_2)}{\ln(R_2/R_1)} \cdot \ln R_1 \cdot \frac{(R_2^2 - R_1^2)}{2} \right. \\ \left. - \frac{(T_1 - T_2)}{2 \cdot \ln(R_2/R_1)} \cdot \left(R_2^2 \ln R_2 - R_1^2 \ln R_1 - \frac{(R_2^2 - R_1^2)}{2} \right) \right] \end{aligned}$$

as the thermal contribution to the radial deformation. Note that the above expression has the form $R\alpha(T_1 - (T_1 - T_2) C_T)$. The term $T_1 (T_1 - T_2) C_T$ is defined as an effective tube temperature.

Equation Definition (Stress)

The following stress definitions are those found in any text presenting the solution of a classical thick-walled cylinder.

Pressure contributions are as follows:

$$S_H = \frac{P_1 R_1^2 - P_2 R_2^2 + \frac{R_1^2 R_2^2}{R^2} (P_1 - P_2)}{R_2^2 - R_1^2}$$

$$S_A = \frac{P_1 R_1^2 - P_2 R_2^2}{R_2^2 - R_1^2}$$

$$S_R = \frac{P_1 R_1^2 - P_2 R_2^2 - \frac{R_1^2 R_2^2}{R^2} (P_1 - P_2)}{R_2^2 - R_1^2}$$

Thermal contributions are:

$$S_H = \frac{E (T_1 - T_2)}{2(1-\nu) \ln(R_2/R_1)} \left\{ 1.0 - \ln(R_2/R) - \frac{R_1^2}{R_2^2 - R_1^2} \left(1.0 + \frac{R_2^2}{R^2} \right) \ln(R_2/R_1) \right\}$$

$$S_A = \frac{E (T_1 - T_2)}{2(1-\nu) \ln(R_2/R_1)} \left\{ 1.0 - 2\ln(R_2/R) - \frac{2R_1^2}{R_2^2 - R_1^2} \ln(R_2/R_1) \right\}$$

$$S_R = \frac{E (T_1 - T_2)}{2(1-\nu) \ln(R_2/R_1)} \left\{ -\ln(R_2/R) - \frac{R_1^2}{R_2^2 - R_1^2} \left(1.0 - \frac{R_2^2}{R^2} \right) \ln(R_2/R_1) \right\}$$

4.2.2 Material Properties (Thermal)

Elastic properties are those presented in Section 4.1.2. Thermal properties employed in this section are presented below.

Temperature	Thermal Conductivity	
	$K_{2\frac{1}{2} \text{ Cr-1 Mo}}$	K_{helium}
400°F	23.65	0.122
500	23.31	0.132
600	22.89	0.141
700	22.39	0.149
800	21.79	0.158
900	21.12	0.166
950	20.76	0.170

4.2.3 Stress Analysis

Pressure and thermal stress components* are established for the superheater steady state condition. The thermal boundary conditions and applied pressure loads are:

Node Locations	Pressure		
	Steam	Helium	Sodium
2	1595 psi	260 psi	
4	1595	260	120 psi
26	1560	260	140
86	1560	260	140
110	1525	260	160
126	1525	260	160
128	1525	260	

* Pressure stress components established here are hoop and radial only. Axial stresses due to pressure loading are included in the tube-tube-shell interaction analysis (Section 4.1).

Thermal Boundary Conditions

Node Location	T ₁	Node Location	T ₄
2	613*		
4	722	204	842
26	801	226	882
86	839	286	898
110	897	310	923
126	923	326	934
128	909*		

* Isothermal

The resultant stress components are presented in Tables 4-3 through 4-6.

TABLE 4-3

INNER TUBE PRIMARY PRESSURE STRESS RESULTANTS FOR THE SUPERHEATER STEADY STATE CONDITION

Node	Primary Stress	
	Hoop	Radial
2	6170 psi	- 927 psi
4	6170	- 927
26	6000	- 910
86	6000	- 910
110*	4790	- 982
126*	2080	-1215
128	5830	- 892

* Areas of radial interference.

TABLE 4-4

OUTER TUBE PRIMARY PRESSURE STRESS RESULTANTS
FOR THE SUPERHEATER STEADY STATE CONDITION

Node	Primary Stress	
	Hoop	Radial
204	531 psi	- 190 psi
226	418	- 200
286	418	- 200
310*	1140	- 300
326*	3308	- 533

* Areas of radial interference

TABLE 4-5

INNER TUBE SECONDARY STRESS RESULTANTS
FOR THE SUPERHEATER STEADY STATE CONDITION

Node	Secondary Stress		
	Pressure Cont.	Thermal Cont.	
	Hoop	Axial and/or Hoop	
		Inside Dia.	Outside Dia.
2	670 psi	Isothermal	
4	670	6190	-5450
26	650	4430	-3910
86	650	3330	-2940
110	540	1510	-1330
126	310	635	- 560
128	630	Isothermal	

TABLE 4-6

OUTER TUBE SECONDARY STRESS RESULTANTS
FOR THE SUPERHEATER STEADY STATE CONDITION

Node	Pressure Cont.	Thermal Cont.	
	Hoop	Axial and/or Hoop	
		Inside Dia.	Outside Dia.
204	200 psi	7030 psi	-5640 psi
226	230	4570	-4010
286	290	3430	-3010
310	310	1550	-1360
326	330	660	- 575

5.0 CODE EVALUATION

Resultant stresses presented in Section 4.0 are evaluated in accordance with Sections 4.3 (Normal and Upset Conditions) and 5.2b (Strain Limits for Elastic Analysis) of Code Case 1331-8, Nuclear Components in Elevated Temperature.

Criteria for evaluation is as follows:

Load-Controlled Stresses (Primary)

$$P_M \leq S_{MT}$$

$$P_L + P_B \leq \frac{1.5 S_M}{KS_T}$$

Strain Limits

$$\left(P_L + \frac{P_B}{K}\right)_{\max} + Q_{\text{range}} \leq S_q$$

The brief presentation of the above criteria assumes familiarity with the referenced code case. Readers unacquainted with the definitions above are encouraged to consult the code case so that the following results are more fully understood.

5.1 Inner Tube Code Evaluation

TABLE 5-1

INNER TUBE PRIMARY STRESS P_M , $P_L + P_B$ CODE EVALUATION

Axial Constraint - Free

Node	Temp.	P_M	S_{MT}	$P_L + P_B$	KS_T
2	613	8990	17900	8990	25600
4	750	8990	17900	8990	25600
26	825	8940	14200	14010	15480
86	853	6910	12300	12120	13640
110	903	6530	9600	6530	10300
126	926	6820	8450	6820	8850
128	909	6500	9140	6500	9780

TABLE 5-2

INNER TUBE PRIMARY PLUS SECONDARY, $P_L + \frac{P_B}{K} + Q_R$ CODE EVALUATION

Axial Constraint - Free

Node	Temp.	$P_L + \frac{P_B}{K} + Q_R$		S_q
		Inside Dia.	Outside Dia.	
2	613	14470	14150	26600
4	750	15850	2670	26600
26	825	17860	9030	25800
86	853	14680	7980	22870
110	903	8650	4720	18000
126	926	7770	5960	16060
128	909	7985	5610	17250

TABLE 5-3

INNER TUBE PRIMARY STRESS $P_M, P_L + P_B$ CODE EVALUATION

Axial Constraint - Bonded

Node	Temp.	P_M	S_{MT}	$P_L + P_B$	KS_T
2	613	14300	17900	14300	25600
4	750	12150	17900	12150	25600
26	825	10300	14200	10620	15480
86	853	8040	12300	8350	13640
110	903	5750	9600	5752	10300
126	926	4160	8450	4155	8850
128	909	6400	9140	6400	9780

TABLE 5-4

INNER TUBE PRIMARY PLUS SECONDARY, $P_L + \frac{P_B}{K} + Q_R$ CODE EVALUATION

Axial Constraint - Bonded

Node	Temp.	$P_L + \frac{P_B}{K} + Q_R$		S_q
		Inside Dia.	Outside Dia.	
2	613	20790	19460	26600
4	750	19010	6040	26600
26	825	15620	6030	25800
86	853	12260	4730	22870
110	903	7860	3940	18000
126	926	5100	3290	16060
128	909	7980	6130	17250

5.2 Outer Tube Code Evaluation

TABLE 5-5

OUTER TUBE PRIMARY STRESS P_M , $P_L + P_B$ CODE EVALUATION

Axial Constraint - Free

Node	Temp.	P_M	S_{MT}	$P_L + P_B$	KS_T
204	820	3870	14580	3870	17200
226	870	3730	11200	6470	13100
286	888	2180	10140	5180	12100
310	920	2870	8680	2870	10100
326	931	5040	8220	5040	9020

TABLE 5-6

OUTER TUBE PRIMARY PLUS SECONDARY $P_L + \frac{P_B}{K} + Q_R$ CODE EVALUATION

Axial Constraint - Free

Node	Temp.	$P_L + \frac{P_B}{K} + Q_R$		S_q
		Inside Dia.	Outside Dia.	
204	820	7820	8860	26400
226	870	5880	9520	20900
286	888	4570	7140	19170
310	920	3440	2930	16450
326	931	5370	4710	15600

TABLE 5-7

OUTER TUBE PRIMARY STRESS $P_M, P_L + P_B$ CODE EVALUATION

Axial Constraint - Bonded

Node	Temp.	P_M	S_{MT}	$P_L + P_B$	KS_T
204	820	5930	14580	5930	17200
226	870	4620	11200	4720	13100
286	888	3140	10140	3190	12100
310	920	2360	8680	2360	10100
326	931	3840	8220	3840	9020

TABLE 5-8

OUTER TUBE PRIMARY PLUS SECONDARY $P_L + \frac{P_B}{K} + Q_R$ CODE EVALUATION

Axial Constraint - Bonded

Node	Temp.	$P_L + \frac{P_B}{K} + Q_R$		S_q
		Inside Dia.	Outside Dia.	
204	820	7820	10920	26400
226	870	5480	8170	20900
286	888	4400	5650	19170
310	920	3440	2440	16450
326	931	5200	2960	15600

5.3 Sample Calculations Demonstrating the Stress Complication Procedure

Primary stress components shown in Tables 5-1, 5-3, 5-4 and 5-7 have been extracted without alteration from Tables 4-1 and 4-2. A sample complication demonstrating the primary plus secondary stress intensity is as follows:

Example - Node 26, Table 5-2

Inner Tube Primary Plus Secondary Stress Complication

Axial Constraint - Free

P_L	$\frac{P_B}{K}$	Q_R	$P_L + \frac{P_B}{K} + Q_R$
8030	$\frac{R_1}{R_2} \cdot \frac{5070}{1.09}$	4430	16301 (Axial)
6000	--	650 + 4430	11080 (Hoop)
-910		-650	-1560 (Radial)

* Ratio inner to outer radii = 0.826

The resultant maximum stress intensity is 17861 psi.

6.0 REFERENCES

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