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FLOW-INDUCED VIBRATION STUDY
IN THE LOFT STEAM GENERATOR

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RESEARCH, ENGINEERING AND CONSTRUCTION REPORT ENGINEERING ANALYSIS DIVISION

THERMAL ANALYSIS

FLOW-INDUCED VIBRATION STUDY IN THE LOFT STEAM GENERATOR

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IDAHO NATIONAL ENGINEERING LABORATORY
LOFT TECHNICAL REPORT
LOFT PROGRAM

TITLE FLOW-INDUCED VIBRATION STUDY IN THE LOFT STEAM GENERATOR		REPORT NO. LTR # 1141-30 RE-A-77-045
AUTHOR C. F. Carmichael <i>C. F. Carmichael / map</i>	GWA NO. 52151-543-382	
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SUMMARY

The consequences of flow induced vibration in the LOFT steam generator were studied. Tube-baffle contact and fretting wear are expected to occur while tube-tube contact is not predicted. The LOFT steam generator is, in all probability adequate from a fluid induced viewpoint for the scheduled service of the LOFT facility at power.

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1.0 INTRODUCTION

1.1 Description of System

The LOFT Steam Generator⁽¹⁻¹⁰⁾⁽¹¹⁾ is a vertical U-tube type heat exchanger which transfers heat generated in the reactor core, from the primary to the secondary coolant system. Thermal-hydraulic design parameters of the steam generator are given in Table I. A sketch of the tube-bundle dimensions, based on the referenced drawings, appears in Figure 1.

1.2 Purpose of the Analysis

Vibration of the straight sections as well as the U-bends of the steam generator tubes, results from transient forces due to steam-water flow past the tubes. The purpose of the analysis is to identify the important fluid-induced vibration (FIV) mechanisms and the resulting forces acting on the tubes, to determine those regions of the tube bundle which have the largest-amplitude motions in response to FIV forces, and to decide whether tube-baffle contact or tube-tube collision occurs under the given flow conditions.

2.0 METHOD OF ANALYSIS

The consequences of flow-induced vibrations (FIV) for the LOFT Steam Generator, were investigated for a limited number of cases that were considered to be likely or potential problem areas. The assumptions and general basis for developing these cases are covered below in the Discussion. Due to the extremely large number of possible combinations of physical parameters that could be investigated, no attempt was made to provide an exhaustive study of all combinations; nor was such an exhaustive study considered necessary, especially in view of the many uncertainties that still exist in this field.

TABLE I

LOFT Steam GeneratorThermal-Hydraulic Parameters

Total Number of U-Tubes (2 straight sections each)	- 1845
Tube Side (Primary Coolant System) Nominal Pressure	- 2250 psia
Shell Side (Secondary Coolant System) Nominal Pressure	- 850 psia
Tube Side Nominal Mass Flowrate	2.1×10^6 lbm/hr.
Tube Side Maximum Mass Flowrate	3.9×10^6 lbm/hr.
Shell Side Minimum Mass Flowrate	4.39×10^5 lbm/hr. (34)
Shell Side Maximum Mass Flowrate	6.59×10^5 lbm/hr. (34)
Tube Material	Inconel - 600
Spacing	Equilateral Triangle
Tube ID/OD	0.402/0.500 inches
Tube Wall Thickness	0.049 inches (#18 BWG)
Tube Pitch	0.75 inches
Length of Straight Section, Up to but not including U-Bend	84 inches (includes tubesheet)
U-Bend Maximum Diameter (Between Centers)	49.5 inches
U-Bend Minimum Diameter (Between Centers)	3.0 inches
Number of Shell-Side Baffles	3 (not including End Support Plate Baffle)
Baffle Spacing	17.375 inches (evenly spaced)

FIGURE 1

SCHEMATIC OF LOFT STEAM GENERATOR

TUBE BUNDLE ASSEMBLY

REF. LOFT DRAWINGS (F-10)

46 1513

10 X 10 TO THE CENTIMETER 13 X 25 CM.
 KEUFFEL & ESSER CO. MADE IN U.S.A.

The method of analysis which evolved, was as follows:

1. The three most important probable FIV excitation mechanisms were identified (von Karman vortex shedding, turbulent buffeting, and fluidelastic excitation). The first two mechanisms were considered separately, since they interfere with each other, and the third was assumed to originate from either one of the others, so that it also could be considered separately.
2. Shell-side flow velocities for the expected operating conditions were estimated for each tube bay in the straight-tube baffle sections (Appendix H), and the U-tube bend region (Appendix F). These velocities are presented in Figures 2 and 3, respectively.
3. Critical flow velocities for the onset of fluidelastic instability were calculated (Appendix C) and are presented in Figure 4.
4. Tube damping ratios in the ranges measured by Halle et al.⁽²³⁾ were used to scope the expected results.
4. Forcing-function frequencies and amplitudes were estimated for the vortex-shedding mechanisms (Appendix A), based on the work of Y. N. Chen⁽¹⁴⁾⁽¹⁵⁾⁽¹⁶⁾ and the flow velocities estimated previously.
5. Turbulent-buffeting mechanism estimated forcing frequencies and amplitudes were based on the flow velocities, and on the work of P. R. Owen⁽¹⁷⁾ and A. A. Townsend⁽¹⁸⁾.
6. Tube natural frequencies were estimated, based on the developments summarized in Shin and Wambsganss⁽¹²⁾ and in Thomson⁽³¹⁾.
7. Tube-baffle contact was predicted by assuming several cases for the longest possible unsupported tube spans and comparing forcing

frequency, tube natural frequency, tube amplification factor (consider as a single-degree-of-freedom system), and tube deflection, with baffle clearance. These results are summarized in Figure 5 and Appendix A.

8. Tube-to-tube collision in the straight-tube section was predicted not to occur from either mechanism (vortex shedding or turbulent buffeting).
9. The longest remaining unsupported tube spans of interest at this point, were located in the U-tube bend region at the top of the steam generator. Two structural models then were generated with the SAP4 code, in order to study the maximum deflection responses of the U-tube bends in this region (summarized in Appendix G). These results show that small finite tube motions do exist resulting in fretting wear on the tubes, baffles and tube support spaces; however, tube-to-tube collision does not occur here for the given operating conditions.

FIGURE 2

LOFT STEAM GENERATOR
SHELL SIDE FLOW VELOCITIES
AND DYNAMIC PRESSURES

- LINEAR QUALITY GRADIENT -

RADIAL CROSSFLOW VELOCITIES
 AT CENTERLINE:

○ - $\dot{m} = 183 \text{ LBm/SEC}$

△ - $\dot{m} = 122 \text{ LBm/SEC}$

DYNAMIC PRESSURES
 IN CROSS FLOW, AT
 CENTERLINE:

□ - $\dot{m} = 183 \text{ LBm/SEC}$

X - $\dot{m} = 122 \text{ LBm/SEC}$

FIGURE 5
VORTEX SHEDDING FREQUENCY
FOR STRAIGHT TUBE REGION.

3.0 DISCUSSION

3.1 Previous Related Flow-Induced Vibration Studies

Messrs. Shin and Wambsganss ⁽¹²⁾ have published a state-of-the-art review of flow-induced vibration (FIV) in LMFBR steam generators, which has influenced this analysis to a considerable extent.

Some of their more important findings were as follows:

- (a) crossflow has a much higher potential than parallel flow for causing tube vibration damage;
- (b) an increase of tube-baffle hole clearance causes decreased tube natural frequency;
- (c) shell-side flow represents the primary source of flow-induced vibration;
- (d) anti-vibration bar regions and U-tube bend regions are vulnerable to FIV damage;
- (e) FIV forcing mechanisms include vortex shedding, turbulent buffeting, fluidelastic whirling, jet switching, and system-dependent sources (structural-borne noise and flow oscillations);
- (f) the state of the art is inadequate to predict accurate shell-side flow velocity distributions;
- (g) added mass of fluid, internal pressurization of tubes, and U-tube bend curvature all affect tube natural frequency and must be accounted for;
- (h) tube natural frequencies should be separated from shedding frequencies by a factor of 3 if flow velocities cannot be predicted accurately;

- (i) dominant turbulent-buffeting frequency should be separated from the tube natural frequencies,
- (j) tube natural frequencies must be greater than the vortex shedding frequency, dominant turbulent-buffeting frequency, and fluidelastic critical whirling frequency,
- (k) maximum expected tube displacement must be less than half the tube gap in order to avoid tube-to-tube contact,
- (l) maximum combined stresses due to FIV loads plus thermal and gravity loads, must not exceed the tube fatigue-endurance limits, and
- (m) sufficient cycles should be available to avoid tube failure due to wear at baffle support points.

Savkar⁽¹³⁾ studied the effects of added mass, vortex shedding, turbulent buffeting, and motion-dependent instabilities. He concluded that several unresolved issues still exist:

- (a) the effect of separated crossflow on added mass,
- (b) the effect of ignoring the Reynolds Number in unsteady fluid motion, and
- (c) the explanation of vortex-shedding "lock-in" at resonance.

In addition, Savkar shows that the added mass corrections due to Fritz⁽¹⁴⁾ ignore the effect of frequency-dependent drag force on the tube. The value of the fluctuating vortex-shedding drag coefficient at twice the Strouhal frequency is given as the order of 0.2 (comparable to the values given by Shin and Wambsganss). Vortex-shedding lift force measurements are shown to mutually repel neighboring cylinders, opposite to the predictions of potential flow theory.

Y. N. Chen⁽¹⁴⁾⁽¹⁵⁾⁽¹⁶⁾ reported vortex-shedding lift coefficient and Strouhal Number values for tube bundles with both staggered and in-line spacing. There is apparently disagreement between Chen and Owen⁽¹⁷⁾ as to whether the predominant fluid forcing mechanism deep within a tube bundle is vortex-shedding or turbulent-buffeting (or perhaps fluidelastic instability). The vortex-shedding calculations on the LOFT Steam Generator were based on Chen's work.

P. R. Owen⁽¹⁷⁾ derived an expression for the dominant turbulent-buffeting mechanism frequency in crossflow. A. A. Townsend⁽¹⁸⁾ measured turbulence intensity levels in air flow downstream of a transverse circular cylinder; his results were also reported by J. O. Hinze⁽¹⁹⁾.

Fluidelastic mechanisms in tube arrays (whirling instabilities) were investigated by H. J. Connors,⁽²⁰⁾ R. D. Blevins,⁽²¹⁾ and S. S. Chen.⁽²²⁾

U-tube critical damping ratios were measured by Halle et al.⁽²³⁾ K. P. Singh⁽²⁴⁾ developed a model for flow velocities in the U-bend region of a tube bundle. Kays and London⁽²⁵⁾ reported pressure drop information for tube bundles which was used in this analysis. Tinker⁽²⁶⁾ investigated the shell-side flow characteristics of heat exchangers. The work of Gerlach and Dodge;⁽²⁷⁾ Chen, Rosenberg and Wambsganss;⁽²⁸⁾ and Chen and Weber,⁽²⁹⁾ provided additional background for the present study.

3.2 Assumptions Made in The Present Flow-Induced Vibration Study

There are an almost infinite number of possible combinations of fluid forcing mechanisms, flow conditions, baffle misalignments, critical damping ratios, turbulence intensities, and tube natural frequencies, that could be investigated in a flow-induced vibration study of the LOFT Steam Generator. In order to reduce the number of cases to be studied in detail to a manageable level, the findings of Shin and Wambsganss,⁽¹²⁾ and Savkar⁽¹³⁾ were

used as a guide. The major assumptions that were made for this study, were as follows:

- (a) the effects of tube-side flow (parallel flow) could be ignored;
- (b) system-dependent excitation mechanisms (structural-borne noise and unsteady-state flow oscillations) were neglected;
- (c) the excitation mechanisms of von Karman vortex shedding and turbulent-buffeting were considered to interfere with one another and therefore could be considered separately;
- (d) the important FIV exciting mechanisms were considered to be (1) von Karman vortex shedding, (2) turbulent buffeting, and (3) fluidelastic excitation resulting from (1) and (2);
- (e) acoustic resonance of the heat exchanger shell with the exciting mechanisms could be ignored, due to the relatively small shell diameter in the region of gas (steam) flow, and low flow velocities; and
- (f) the U-tube bend region was a critical location for FIV.

4.0 RESULTS

Results of this study indicate the existence of general tube-baffle contact throughout the LOFT Steam Generator, except for the lowest baffle. Tube-to-tube collision, acoustic resonance, and fluidelastic instability are not predicted.

Estimated cross-flow shell-side velocities in the straight-tube sections of the bundle at the centerline are presented in Figure 2. Straight-tube sections on the bundle periphery are expected to see lower cross-flow velocities than these, due to the combined effects of the 3/16" diameter baffle-perforation leakages and turning of the flow at the outer edges of the bundle.

Estimated flow velocities are given in Figure 3 for the U-tube region. Selected tube natural frequencies are given in Tables II (straight sections) and III (U-bend region), as well as Appendix D.

TABLE II*
Natural Frequencies of Straight-Tube Sections
of LOFT Steam Generator Bundle

(Beam No.) and Assumed Tube-Section Boundary Conditions	Unsupported Span Description	Unsupported Span (in.)	fn = Natural Frequency (Hz)	Mode No.
(1) U-Tube Cantilevered from Tube Sheet	No Baffle Contact-Entire U-Tube Cantilevered	96.77 in.	11.5 Hz	1
			9.2	2
			25.7	3
(2) Contact Between U-Tube and Lower Baffle (Plate 8-1)**	U-Tube Cantilevered from Lower Baffle (Plate 8-1)	79.40 in.	2.2	1
			13.6	2
			38.1	3
(3) Contact Between U-Tube and Middle Baffle (Plate 8-2)	Cantilever U-Tube from Middle Baffle (Plate 8-2)	62.03 in.	3.6	1
			22.6	2
			63.3	3
(4) Contact Between U-Tube and Upper Baffle (Plate 8-1)	(a) Cantilever U-Tube from Upper Baffle (Plate 8-1)	44.66 in.	6.9	1
			43.3	2
			121.3	3
	(b) Clamped-Hinged U-Tube below Upper Baffle (Plate 8-1)	52.125 in.	26.50	1
			77.40	2
			156.80	3
(5) Contact Between U-Tube and End Support Baffle (Plate 8-9)	(a) Cantilever U-Tube Above End Support Plate (8-9)	27.285 in.	18.4	1
			115.5	2
			323.4	3
	(b) Clamped-Hinged U-Tube Below End Support Baffle	69.50 in.	17.40	1
			45.00	2
			89.50	3
(6) Contact Between U-Tube and both the Upper and Lower Baffles (8-1)	Simply Supported Tube Be- tween Both (8-1) Baffles (Hinged-Hinged)	34.75 in.	38.30	1
			137.40	2
			296.90	3
(7) Contact Between U-Tube, End Support Baffle (8-9), and Lower Support Baffle (8-1).	Simply Supported Tube from End Support Baffle (Plate 8-9) to Lower Support Baffle (Plate 8-1) (Hinged-Hinged)	52.125 in.	19.90	1
			64.00	2
			137.80	3

† - Pressurization of Tubes Accounted For.

* - See also Appendix D for details.

** - Baffle numbers refer to Figure 1 and the LOFT Drawings (1-10)

TABLE III*

Natural Frequencies of U-Tube Bend for Out-of-Plane Motion of the
 Largest U-Bend ($\lambda = \pi (24.75) + 17.375 = 95$ in.)

U-Bend Boundary Conditions	Mode No.	$f_n =$ Natural Frequency (Hz)
Both Ends Fixed	1	18.2
(Cantilevered;	2	39.2
Clamped-Clamped)	3	79.5
	4	128.7
Both Ends Simply Supported	1	---
(Hinged-Hinged)	2	42.6
	3	71.6
	4	110.9
One End Fixed, The Other Simply Supported	1	12.4
(Clamped-Hinged)	2	32.0
	3	68.8
	4	117.5

* - See also Appendix D.

5.0 CONCLUSIONS

1. Tube-baffle contact due to flow-induced vibration exists in the LOFT Steam Generator for all baffles except the lowest one, for the given operating conditions.
2. Fretting is expected to occur at those tube-baffle locations considered in this study. Fretting is the only result of concern at power operation and can result in baffle hole enlargement and/or tube damage; however, fretting is not expected to be significant in the LOFT Steam Generator because (1) similar steam generators operating at higher power levels and flow apparently do not have serious fretting problems, and (2) the scheduled operation time at power is short.
3. Tube-to-tube collision is not predicted in the LOFT Steam Generator, for the given operating conditions.
4. Fluidelastic instability is not predicted in the LOFT Steam Generator for the given operation conditions.
5. Acoustic resonance of the LOFT Steam Generator shell with one of the flow exciting mechanism, is not predicted.

6.0 RECOMMENDATIONS

Additional structural and hydraulic analyses are not recommended (1) because of the inadequacy of accurately predicting the required forcing function in the two-phase fluid regime, and (2) the short operation times the steam generator will be operating at power. (The LOFT steam generator should not suffer failure due to tube vibration during its intended operational life unless caused by gross flow instability within the steam generator. Gross flow instability would cause more severe problems in operating the plant and should not occur without being detected.)

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APPENDIX A

von Karman Vortex (Vortex-Shedding) Excitation

Mechanism for Flow-Induced Vibration (FIV)

TABLE A-I

SUMMARY OF LOCK-IN MATCHES BETWEEN KARMAN VORTICES AND
TUBE NATURAL FREQUENCIES IN CROSS FLOW

A. Top of Bundle ($63 < f_s < \text{Hz}$), centerline

<u>Case No.</u>	<u>Beam No.</u>	
1.	3-3	Cantilevered U-Tube from Middle Plate 8-2 ($\ell = 62.03 \text{ in.}$) $f_{n_3} = 63.3 \text{ Hz}$
2.	4a-2	Cantilevered U-Tube from Upper Plate 8-1 ($\ell = 44.66 \text{ in.}$)
	4a-3	$f_{n_2} = 43.3 \text{ Hz}$ $f_{n_3} = 121.3 \text{ Hz}$
3.	5b-3	(Clamped-Hinged) Tube Below End Support Plate ($\ell = 69.50 \text{ in.}$) $f_{n_3} = 89.5 \text{ Hz}$
4.	5b-2	(Clamped-Hinged) Tube Below End Support Plate ($\ell = 69.50$) $f_{n_2} = 45.0 \text{ Hz}$
5.	7-2	Simply-Supported, (Hinged-Hinged) Tube from ESP 8-9 to Lower SP 8-1 ($\ell = 52.125''$) $f_{n_2} = 64 \text{ Hz}$ $f_{n_3} = 138 \text{ Hz}$

B. Middle Bay, ζ ($27.9 < f_s < 30.3$ Hz)

<u>Case No.</u>	<u>Beam No.</u>	
6.	1-3	Entire U-Tube Cantilevered from Tube Sheet ($\ell = 96.77$ in.) $f_{n_3} = 25.7$ Hz
7.	2-3	Cantilevered U-Tube from Lower Plate 8-1 ($\ell = 79.40$ in.) $f_{n_3} = 38.1$ Hz
8.	3-2	Cantilevered U-Tube from Middle Plate 8-2 ($\ell = 62.03$ inc.) $f_{n_2} = 22.6$ Hz.
9.	4b-1	Clamped-Hinged Tube Below Upper Plate 8-1 ($\ell = 52.125$ in.) $f_{n_1} = 31.2$ Hz
10.	5b-2	Clamped-Hinged Tube Below ESP ($\ell = 69.50$ in.) $f_{n_2} = 45.0$ Hz.
11.	6-1	Simply-Supported, (Hinged-Hinged) Tube Between Both 8-1 SP's ($\ell = 52.125$ in.) $f_{n_2} = 64$ Hz.

C. Lower Bay, ζ ($4.8 < f_s < 7.2$ Hz)

13. 1-2 Entire U-Tube Cantilevered from Tube Sheet
 ($\ell = 96.77$ in.)
 $f_{n_2} = 9.2$ Hz.
14. 5b-1 Clamped-Hinged Tube Below ESP
 ($\ell = 69.50$ in.)
 $f_{n_1} = 17.4$ Hz.

LOFT STEAM GENERATOR LTR 1141-30
CROSS FLOW KARMAN VORTEX-SHEDDING FREQUENCIES A-4

$$S = \frac{fD}{u_r} = 0.29 \text{ (for } X_L = X_G = 1.5) \quad D_t = 0.5 \text{ m.}$$

Mass
Flowrate

$$\dot{m}_c = 122$$

$$\dot{m}_c = 183$$

$Z =$
 a_x
Loc.

(Top
Bay,
C)

$$u_r$$

$$f_s = \frac{(12)(.29) u_r}{(0.5)}$$

$$f_s = 6.96 u_r \text{ Hz}$$

$$9.1 \text{ fps}$$

$$63.3 \text{ Hz}$$

$$9.42 \text{ fps}$$

$$65.6 \text{ Hz}$$

$$69.5''$$

u_r

(Middle
Bay,
C)

$$u_r$$

$$f_s$$

$$4.01 \text{ fps}$$

$$27.9 \text{ Hz}$$

$$4.36 \text{ fps}$$

$$30.3 \text{ Hz}$$

$$34.75''$$

u_r

(Lower
Bay,
C)

$$u_r$$

$$f_s$$

$$q$$

$$V = V_f$$

$$0.69 \text{ fps}$$

$$4.8 \text{ Hz}$$

$$1.04 \text{ fps}$$

$$7.2 \text{ Hz}$$

$$.02105 \text{ } \frac{1}{\text{mm}}$$

$$S = \frac{fD}{V} = 0.29 \text{ for } X_t = 1.5$$

$$S = 0.29$$

$$X_t = \frac{T}{d} = \frac{0.75}{0.5} = 1.5$$

$$X_l = \frac{L}{d} = \frac{1.299}{0.5} = 2.6$$

- (14) Chen, Y. N., Flow-Induced Vibration and Noise in Tube-Bank Heat Exchangers Due to von Karman Streets, J. Eng. Ind. V. 90 (1), pp 134-146 (Feb 1968)

C_L in Bundle (LIFT FORCE COEFFICIENT)

WIK 1141-50

3/2/77

A-6

C_L in bundle.

$$\dot{m} = 183 \text{ lbm/sec.}$$

$$\sigma = \text{Solidity Ratio, } \left(1 - \frac{A_{\text{flow}}}{A_{\text{total}}}\right) = \frac{0.5}{0.75} = \frac{2}{3} = 0.667.$$

$$\alpha = \text{Flow area ratio} = \left(\frac{A_f}{A_T}\right) = 1 - \sigma = 0.333 = \frac{1}{3}.$$

$$X_L = X_t = \frac{P}{D} = \frac{0.75}{0.5} = 1.5$$

$$C_L \approx 0.28 \text{ (Fig. 6, Chen}^{(15)})$$

- (15) Chen, Y.N., "Fluctuating Lift Forces of the von Karman Vortex Streets on Single Circular ~~Cylinders~~ Cylinders and in Tube Bundles, Part 3 - Lift Forces in Tube Bundles," Journal of Engineering for Industry, May 1972, pp. 623-628. (p. 626)

Strouhal Number for Tube Bundle, Chen (1):

$$St = 0.29 = \frac{f_s D}{u_r}$$

$$f_s = St \left(\frac{u_r}{D} \right) = \frac{(0.29)(9.42 \text{ ft/sec})(12)}{(0.5) \text{ in}} = \frac{65.6}{12} \text{ Hz} = 5.47 \text{ Hz} \text{ for } 183 \frac{\text{in}}{\text{sec}}$$

$$= \frac{63.3}{12} \text{ Hz} = 5.28 \text{ Hz} \text{ for } 172 \frac{\text{in}}{\text{sec}}$$

Lift Force for Top of Tube Bundle, Chen (1):

$$C_L = 0.28 \text{ for } X_L = X_t = \frac{0.75''}{0.50''} = 1.5$$

$$L_o = C_L q S_T$$

$= 17 \frac{3}{8}'' - \frac{1}{2}''$ Span $\rightarrow S_T = L_T D_T = (16 \frac{7}{8}'')(0.5) = 8.4375 \text{ m}^2 = 0.05859 \text{ ft}^2$

$$q = \frac{\rho V^2}{2g_c} = \frac{\rho u_r^2}{2g_c} = \frac{(13.62)^2}{(288 \frac{\text{m}^2}{\text{ft}^2})(32.17 \frac{\text{ft}}{\text{sec}^2})(0.1915 \text{ ft})} = 10.7227 \text{ psi} = 10.41 \text{ lbf/ft}^2$$

$$q = 10.7227 \text{ psi} = 10.41 \text{ lbf/ft}^2$$

$$L_o = C_L q S_T = (0.28)(10.41)(0.05859) = 0.1707 \text{ ft}$$

Lift Force,

$$L = L_o \sin 2\pi f_s t = 0.1707 \sin \left[2\pi (5.47) t \right]$$

Amplification Factor, $AF = \left(\frac{X}{X_o} \right) = \frac{1}{\sqrt{[1 - (\frac{\omega}{\omega_n})^2]^2 + [2(\frac{\omega}{\omega_n})\zeta]^2}}$

APPENDIX B

Turbulent-Buffering Excitation Mechanism For
Flow-Induced Vibration (FIV)

Effective Turbulence Frequency,

The turbulent - buffeting forcing frequency was taken from Owens' work,⁽¹⁷⁾ as

$$\left(\frac{\nu LT}{U_1 d} \right) \approx \frac{1}{3} C_D \left(\frac{U_1}{q'_t} \right)^3 \left(1 - \frac{d}{T} \right)^2,$$

where ν = turbulent - buffeting frequency (Hz),

U_1 = gap velocity over tubes,

T = tube bundle transverse spacing,

d = tube O.D.,

L = tube bundle longitudinal spacing
(in flow direction),

q'_t = effective turbulence-intensity dynamic velocity head.

For $U_1 = 9.42$ ft/sec (top of bundle),

$$\left(\frac{q'_t}{U_1} \right) = 0.5 \quad \left(\text{since } \left(\frac{q}{U_1} \right)^2 = 0.25 \right),$$

the resulting turbulent - buffeting frequency is

$$\nu = 41.3 \text{ Hz}.$$

Turbulence Intensity

measured turbulence intensity for the fully-developed wake of a circular cylinder in airflow, was on the order of 25% of the dynamic velocity head.⁽¹⁸⁾ This value was assumed for the LOFT: - Steam Generator tubes as well.

Turbulent - Buffeting Drag Coefficient

The steady-state drag coefficient value of 1.2 was assumed for the turbulent-buffeting drag coefficient. ... Better information for the force coefficient was not found in the literature.

MEASURED TURBULENCE INTENSITY

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OF WAKE BEHIND CIRCULAR CYLINDER

The measurements were made at various sections in the wake at relative distances from $\xi_1 = 80$ up to 950. Most of the measurements refer to free-stream velocity $U_0 = 1,280$ cm/sec and to a cylinder 0.159 cm in diameter; some to a cylinder 0.953 cm in diameter.

It has been mentioned in the previous section that self-preservation in the detail structure of the turbulence at various sections is attained only at large distances downstream from the cylinder, say, beyond $\xi_1 = 500$. However, not all the data that we want to show here refer to such large distances. We shall consider these data, anyhow, since the information to be gained from their behavior is of sufficient interest, notwithstanding some lack in self-preservation.

FIG. 6-5. Relative turbulence intensities at the sections $\xi_1 = 500, 650, 800$, and 950 in the wake of a circular cylinder. (Townsend, A. A., *Australian J. Sci. Research*, vol. 2, p. 451, 1949.)

Figure 6-5 shows the values of the squared relative turbulence intensities $\overline{u_1^2}/\overline{U_{1,\max}^2}$, $\overline{u_2^2}/\overline{U_{1,\max}^2}$, and $\overline{u_3^2}/\overline{U_{1,\max}^2}$. The curves represent the average values for the four sections at $\xi_1 = 500, 650, 800$, and 950 , respectively. The differences between the quantities at these sections are small and are within experimental scatter; so similarity among the various curves is good indeed.

In Fig. 6-6 are shown the courses of the shear stress $\overline{u_1 u_2}/\overline{U_{1,\max}^2}$ and of the eddy viscosity $(\epsilon_m)_{11}/U_0 d$, in Fig. 6-7 those of the lateral transport quantities $\overline{u_1^2 u_2}/\overline{U_{1,\max}^3}$, $\overline{u_2^2}/\overline{U_{1,\max}^3}$, and $\overline{u_3^2 u_2}/\overline{U_{1,\max}^3}$.

The distribution curves of $\overline{u_1^2 u_2}/\overline{U_{1,\max}^3}$ and $\overline{u_3^2 u_2}/\overline{U_{1,\max}^3}$ show negative parts in the center region of the wake, which means an inward transport to the axis of the wake. This picture accords with the course of the intensity gradients shown in Fig. 6-5, though closer observation of the respective curves reveals that the regions of inward transport and of positive intensity gradients in the center of the wake do not entirely

ICE

very great, and since, in fact, it is difficult to decide what is the correct transport theory, the nature of the velocity distribution in $(\xi_2)_0 = 0.48$. In transport theory we take

$\sqrt{2}$

ory, $c_\gamma = c_w$, the agreement is better a large part of the wake, within the wake boundary region.

Measured
Momentum transport theory $c_\gamma = c_m$
Momentum transport theory $c_\gamma = c_m \sqrt{2}$
Vorticity transport theory $c_\gamma = c_w$
 $(\epsilon_\gamma)_{22} = \text{Constant}$

Wake of a circular cylinder. (Fage, A., *Revue de l'Aviation*, 1935.)

$(\epsilon_\gamma)_{22}$ be calculated from it with the aid of the relation (6.10) constant value of $(\epsilon_\gamma)_{22}$ across the wake, $\approx 0.12 U_0 d$. This is almost twice Taylor's vorticity-transport theory $= 2(\epsilon_m)_{11}$. It gives the best agreement, outside the wake, for $(\epsilon_\gamma)_{22} = 0.119 U_0 d$. The

Quantities in the Wake Flow of a

of these quantities have been made available in a series of publications.

Tube - Baffle Contact from Turbulent - Buffeting Mechanism

B-4

1. Lower Bay (Cantilever), $l = 17.375''$ assumed

$$\zeta = .002$$

$$\text{rad } d = .015625''$$

$$f_n = 127.6 \text{ cps}$$

$$f_t = \left(\frac{1.04}{9.42} \right) (41.3) = 4.6 \text{ Hz}$$

$$ur = 1.04 \text{ fps}$$

$$f_s = \frac{(0.29)(1.04)(12)}{(0.5)} = 7.2 \text{ Hz}$$

$$\zeta = .00555, \quad \zeta_t = 0.25\zeta$$

$$w_t = (0.25)(.00555)(1.2)(0.5) = .000832 \frac{\text{lb}_f}{\text{in}}$$

$$w_s = (.00555)(0.28)(0.5) = .000777 \frac{\text{lb}_f}{\text{in}}$$

(a) Turbulent - Buffet Mechanism:

$$\delta_{sst} = \frac{w_t l^4}{8EI} = \frac{(.000832) \left(\frac{\text{lb}_f}{\text{in}} \right) (17.375)^4 \text{ in}^4}{(8) (29.4 \times 10^6 \frac{\text{lb}_f}{\text{in}^2}) (.001786 \text{ in}^4)}$$

$$\delta_{sst} = .000181 \text{ in.}$$

$$AF_t = \frac{1}{\sqrt{\left[1 - \left(\frac{w_t}{w_n} \right)^2 \right]^2 + \left[2.5 \left(\frac{w_t}{w_n} \right) \right]^2}}$$

$$AF_t = \frac{1}{\sqrt{\left[1 - \left(\frac{4.6}{127.6} \right)^2 \right]^2 + \left[(.002)(2) \left(\frac{4.6}{127.6} \right) \right]^2}}$$

$$AF_t = 1.001$$

$$\delta_t = (1.001)(.000181) = .000181 \text{ in.} \quad \therefore \text{No baffle-tube contact in lower bay.}$$

Tube - Baffle Contact2. Middle Bay

$$q = .0232 \text{ psi}$$

$$U_r = 4.36 \text{ fps}$$

Tube considered as a
 at lower end, simple support upper end;
 cantilever beam, 69.5 inches
 long. (4 spans of 17.375" each)

In general, the crossflow load in one direction will cancel that in the other; however, both **Karman vortex** and turbulent - buffeting loads can act at right angles to the main flow, and that is the case that will be considered.

The load is considered as uniform at the ^{length-weighted} average of the three span loadings.

$$w_{t_1} = (1.2)(0.25)(.05)(.5) = .0075 \text{ lbs/in.}$$

$$w_{t_2} = (1.2)(0.25)(.0232)(.5) = .00348 \text{ lbs/in.}$$

$$w_{t_3} = (1.2)(0.25)(.00555)(.5) = .000833 \text{ lbs/in.}$$

$$\bar{w} = (w_{t_1} + 2w_{t_2} + w_{t_3})\left(\frac{1}{4}\right) = .00383 \text{ lbs/in.}$$

$$f_t = \left(\frac{4.36}{9.42}\right)(41.3) = 19.1 \text{ Hz}$$

$$f_{n_1} = 17.4 \text{ Hz}$$

$$f_{n_1}' = 17.4 \text{ Hz}$$

$$AF = \frac{1}{\sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\zeta\left(\frac{\omega}{\omega_n}\right)\right]^2}}$$

$$AF = \frac{1}{\sqrt{\left[1 - \left(\frac{19.1}{17.4}\right)^2\right]^2 + \left[2(0.002)\left(\frac{19.1}{17.4}\right)\right]^2}}$$

$$AF = 4.88$$

$$\delta_{ss} = \frac{\bar{w} l^4}{185 EI} = \frac{(.00383 \frac{\text{lb}_f}{\text{in}})(69.5)^4 \text{ in}^4}{(185)(29.4 \times 10^6 \frac{\text{lb}_f}{\text{in}^2})(.001786 \text{ in}^4 \left(\frac{21}{15}\right)^2)}$$

$$\delta_{ss} = .004693 \text{ in.}$$

$$\delta_t = AF \delta_{ss} = (4.88)(.00469) = .0229 \text{ in.} > .015625 \text{ in.}$$

∴ Tube - baffle impact occurs on the upper 3 baffles.

APPENDIX C

Fluidelastic Instability (Whirling) Excitation
Mechanism for Flow-Induced Vibration (FIV)

$$\left(\frac{U_{crit}}{f_n D}\right) = \left[\frac{2(2\pi)^{1/2}}{(C_x K_y)^{1/4}} \right] \left[\frac{m(2\zeta)}{\rho D^2} \right]^{1/2}$$

$$\left[\frac{2(2\pi)^{1/2}}{(C_x K_y)^{1/4}} \right] \approx 9.0 \text{ for } T/\phi = 1.5 \quad (21)$$

$$\left(\frac{U_c}{f_n D}\right) = 9.0 \left[\frac{m(2\pi\zeta)}{\rho D^2} \right]^{1/2}$$

m = mass per unit length of tubes = .0337 lbm/ft

ρ = fluid density = $\frac{1}{5.9} = \frac{1}{1.915} = 5.222 \text{ lbm/ft}^3$

$$.002 < \zeta < .02$$

$$D = 0.500 \text{ in.}$$

$$\zeta = .002$$

$$\left(\frac{U_c}{f_n D}\right) = 9.0 \left[\frac{(.0337 \frac{\text{lbm}}{\text{ft}})(2\pi)(.002)(.005 \frac{\text{ft}}{\text{lbm}})}{(0.5)^2 \text{ in}^2 \left(\frac{1}{1.915} \right)} \right]^{1/2}$$

$$\left(\frac{U_c}{f_n D}\right) = 6.74 \rightarrow U_c = 6.74 \left(\frac{D}{12}\right)(f_n) = 0.4213 f_n (f_n)$$

(21) Blevins, R.D., "Fluid Elastic Whirling of Tube Rows and Tube Arrays," ASME Paper 76-WA/FE-26, Dec 76.

$$\underline{f = .02}$$

$$\left(\frac{U_c}{f_n D} \right) = 9.0 \left[\frac{(.0837)(2\pi)(.02)(.1915)(1728)}{(0.5)} \right]^{\frac{1}{2}}$$

Units

$$\left[\frac{(\frac{ft}{min}) (\frac{ft}{min}) (\frac{min}{ft}) (\frac{ft}{min}) (\frac{min}{ft})}{(\frac{ft}{min})} \right]^{\frac{1}{2}} = \frac{1}{1}$$

$$\left(\frac{U_c}{f_n D} \right) = 21.31 \rightarrow U_c = 21.31 f_n \left(\frac{D}{12} \right) = 1.3319 f_n (f_{sp})$$

ξ	f_n (Hz)	U_c (g _{rms})
<div style="text-align: center;"> $.002$ $\odot$ </div>	1.0 < 5.0	0.4213 < 2.11
	10.0	4.213
	20.	8.426
	30.	12.64
	40.	16.85
	60.	25.28
	100.	42.13
	150.	63.2
	200.	84.3
	300.	126.4
<div style="text-align: center;"> $.02$ Δ </div>	1.0 < 5.0	1.3319 < 6.66
	10.	13.32
	20.	26.64
	30.	40.00
	40.	53.28
	60.	79.91
	100.	133.2
	150.	199.8
	200.	266.4
	300.	399.6

APPENDIX D

Tube Natural Frequencies and Damping Ratios

A. Natural Frequencies

LTR 1741-30

D-1

Natural frequencies of the LOFT Steam Generator U-Tubes were estimated using the methods outlined by Shim and Wambeganss⁽¹²⁾, as follows:

1. Tube Cross Section Properties:

$$E = 29.4 \times 10^6 \text{ psi (Inconel-600 at } 500^\circ\text{F)} \quad (30)$$

$$I = \frac{A}{4} (R_2^2 + R_1^2) = \frac{\pi}{4} (R_2^2 - R_1^2) (R_2^2 + R_1^2)$$

$$I = \frac{\pi}{4} \left[\left(\frac{.500}{2} \right)^2 - \left(\frac{.402}{2} \right)^2 \right] \left[\left(\frac{.500}{2} \right)^2 + \left(\frac{.402}{2} \right)^2 \right]$$

$$I = .001786 \text{ in}^4$$

Mass per unit length,

$$m = m_{\text{tube}} + m_{\text{internal water}} + \Delta m_h$$

$$m_{\text{tube}} = \left(0.236 \frac{\text{lbm}}{\text{ft}} \right) \left(\frac{\rho_{\text{Inconel-600}}}{\rho_{\text{steel}}} \right) = \left(0.236 \right) \left(\frac{518.5}{(7.28)(2833)} \right)$$

$$m_{\text{tube}} = 0.250 \frac{\text{lbm}}{\text{ft}}$$

$$m_w = m_{\text{internal water}} = \rho_w A_f = \frac{(47.1)(0.1269)}{(144)} = .04151 \frac{\text{lbm}}{\text{ft}}$$

$$\Delta m_h = \left(\frac{a}{c} \right) \pi \rho a^2 \quad (12)$$

The maximum possible value (in liquid water) will be used:

$$\Delta m_h = \left(\frac{0.25}{0.14375} \right) \pi \rho \left(\frac{.25}{12} \right)^2 = 0.1126 \frac{\text{lbm}}{\text{ft}}$$

$$m = 0.250 + .0415 + .1126 = 0.404 \frac{\text{lbm}}{\text{ft}} \times \frac{1}{12} =$$

$$m = .0337 \text{ lbm/in.}$$

2. Base natural frequencies (uncorrected for internal pressurization) :

$$f_n = \frac{(\beta_n l)^2}{2\pi} \sqrt{\frac{(12g_c)(E)(I)}{m l^4}}$$

where $(\beta_n l)^2$ = Boundary-Condition (End-Fixity) Eigenvalue,

f_n = frequency (Hz).

Substituting the appropriate values, we get

$$f_n = (3903.6)(\beta_n l)^2 \left(\frac{1}{l}\right) \text{ Hz.}$$

3. Pressurization Correction Factor :

$$\Delta P = (2250 - 850) = 1400 \text{ psi}$$

$$\Gamma = \frac{F_A l^2}{EI} = \frac{A_F \Delta P l^2}{EI} = \frac{(1400)(.1269)(l^2)}{(29.4 \times 10^6)(.001786)}$$

$$\Gamma = .003383 l^2,$$

where l = unsupported span of tube.

~~The ratio of ^{natural} frequency to uncorrected frequency is read from Table D-I (12).~~

The natural-frequency eigenvalue then is read from Table D-I (12), and is used to correct the unpressurized natural frequency value.

TABLE D-I

Pressurized - Tube Natural Frequency EigenvaluesEnd Conditions

Γ λ_1^* λ_2 λ_3 λ_4

Both Ends Fixed :

-10	19.410	57.808	116.739	195.520
-5	20.949	59.778	118.839	197.702
0	22.374	61.674	120.902	199.860
5	23.704	63.512	122.931	201.994
10	24.957	65.290	124.925	204.107

One End Fixed, the Other Simply Supported :

-10	11.021	45.468	99.635	173.582
-5	13.413	47.770	101.968	173.942
0	15.418	49.965	104.248	178.269
5	17.177	52.067	106.479	180.568
10	18.760	54.083	108.664	182.837

Both Ends Simply Supported :

-9.8	0.830	34.230	83.783	152.935
-5	6.933	36.893	86.290	155.394
0	9.870	39.479	88.826	157.914
5	12.114	41.904	91.292	160.394
10	14.003	44.196	93.693	162.837

* λ_n is the n th eigenvalue $(\beta_n l)^2$ in the expression, $f_n = \frac{(\beta_n l)^2}{2\pi} \sqrt{\frac{EI}{m l^4}}$,
for tube natural frequency.

4. Tube Natural Frequencies:

The resulting tube span natural frequencies are calculated from ~~the~~ the expression

$$f_n' = \frac{\lambda_n}{(\beta_n l)^2} f_n,$$

where f_n = unpressurized tube span natural frequency of mode n ,

λ_n = eigenvalue from Table D-I,

$(\beta_n l)^2$ = eigenvalue for unpressurized tube, ⁽³¹⁾

and f_n' = natural frequency of pressurized tube for mode n .

These results for the LOFI Steam Generator tubes, are given in Table D-II.

TABLE D-II

LOFT Steam Generator U-Tube Natural Frequencies of Vibration

Case No. *	Unsupported Span (inches)	$T' = \left(\frac{F A l^2}{E I} \right) = .003383 l^2$	$\left(\frac{\lambda'_n}{\lambda_n} \right)$	Mode No., n	f_n (Hz)	$f'_n = \left(\frac{\lambda'_n}{\lambda_n} \right) f_n$
(1)	96.77	31.7		1	1.5 Hz	
				2	9.2	
				3	25.7	
(2)	79.40	21.3		1	2.2	
				2	13.6	
				3	38.1	
(3)	62.03	13.0		1	3.6	
				2	22.6	
				3	63.3	
(4a)	44.66	6.75		1	6.9	
				2	43.3	
				3	121.3	
(4b)	52.125	9.19	(18/15)	1	22.1	26.5
			(54/50)	2	71.7	77.4
			(104/104)	3	149.6	156.8
(5a)	27.285	2.52		1	18.4	
				2	115.5	
				3	323.4	
(5b)	69.50	16.3	(21/15)	1	12.4	17.4
			(56/50)	2	40.2	45.0
			(111/104)	3	83.9	89.5
(6)	34.75	4.09	(12/10)	1	31.9	38.3
			(42/39)	2	127.6	137.4
			(92/89)	3	287.2	296.9
(7)	52.125	9.19	(14/10)	1	14.2	19.9
			(44/39)	2	56.7	64.0
			(94/89)	3	127.6	134.8
(8)	17.375	1.02	1.0	1	127.6	127.6
			1.0	2	510.5	510.5
			1.0	3	1148.6	1148.6

* - Case numbers refer to Table II of the main text of this report.

B. Measured Damping Ratios of U-Tubes

Damping ratios of U-tubes as measured by Halle et al.⁽²³⁾ are given in Table D-III. These ratios were measured ~~by the logarithmic decrement and bandwidth methods~~ for bare and finned U-tubes with overhangs ranging from 13 to 89 inches, vibrating in air. The maximum and ~~minimum~~ minimum measured ~~damping~~ damping ratios of .02 and .002 are taken here as representative values to be expected in ^{the} LOFT steam generator.

TABLE D-III.
MEASURED DAMPING RATIOS AND NATURAL FREQUENCIES OF U-TUBES (23)

Test	Length of Overhang, in. (Note 1)	Test Parameters			Frequency Hz	Damping Test Method (Note 5)	Input Amplitude, 10^{-3} in. rms (Note 6)	Damping Ratio, %	Remarks (Note Number)
		Type (Note 2)	Location (Note 3)	Direction (Note 4)					
1a	89	D	U	H	1.14	LD		0.0027	← empty tube 7
1b	89	D	U	H		BW	29	0.0077	
2a	89	D	U	H	3.71	LD		0.0020	
2b	89	D	U	H		BW	38	0.0070	8
2c	89	D	U	H		BW	13	0.0036	8
3	89	D	U	V	6.25	LD		0.0087	
4	89	D	MT	V	20.1	-			15, 16
5a	89 R	D	U	H	3.71	-			
5b	89	D	U	H	3.71	-			
6	89 R	D	U	V	6.13	-			17
7a	89	A	MT	H	19.9	-			15, 16
7b	89	A	MB	H	19.9	-			15, 16
8a	13	A	MB	H	19.5	-			15
8b	13	D	U	H	19.5	-			15
9a	72 R	D	U	H	5.45	-			
9b	72	D	U	H	5.45	-			
10	72 R	D	U	V	8.87	-			17
11a	89	D	U	H	3.75	BW	64	0.0083	9
11b	89	D	U	H	3.75	BW	26	0.0049	9
11c	89	D	U	H	3.75	BW	12	0.0021	9
12a	89	D	U	V	6.24	BW	43	0.0106	10
12b	89	D	U	V	6.27	BW	17	0.0079	10
	89	D	U	V	6.26	BW	8.3	0.0027	10
	89	A	MB	H	20.3	BW	9.5	0.0192	11, 15, 16
	89	A	MB	H	20.3	BW	5.8	0.0174	11, 15, 16
13c	89	A	MB	H	20.3	BW	3.4	0.0104	11, 15, 16
13d	89	D	U	H	20.4	BW	9.5	0.0190	12, 15, 16
13e	89	D	U	H	20.4	BW	5.8	0.0126	12, 15, 16
13f	89	D	U	H	20.3	BW	3.4	0.0098	12, 15, 16
14	89	D	U	H	3.76	LD		0.0166	18
15	89	D	U	V	6.64	LD		0.0229	18
16	89	D	U	H	3.96	BW	2.5	0.0138	19
17a	36 S	D	U	H	9.63	BW	9.3	0.0113	13
17b	36 S	D	U	H	9.65	BW	4.5	0.0117	13
17c	36 S	D	U	H	9.66	BW	3.2	0.0077	13
17d	36 S	A	MB	H	9.60	BW	9.3		
17e	36 S	A	MB	H	9.66	BW	4.5	0.0115	14
17f	36 S	A	MB	H	9.67	BW	3.2	0.0085	14
18	36 S	D	U	V	15.7 and 11.3				

Explanation of Notes:

1. R designates slotted restraint installed 13 in. from U-bend end. S designates special TSA spacing (see text).
2. D designates displacement measured by means of optical tracker. A designates determination from accelerometer signals.
3. Refers to location of measurement. U designates the U-bend end. MT and MB designate the midspan location between the second and third TSA's, on the top and bottom tubes, respectively.
4. V (vertical) and H (horizontal) correspond, respectively, to vibratory motion in and out of the plane of the U-bend.
5. LD designates the log-decrement and BW the bandwidth method of damping determination.
6. Average input amplitude applied by vibration exciter in horizontal direction at tube ends opposite to the U-bend. Empty tube (no water fill).
14. Seven sets of damping determinations performed at two or three different levels of input excitation. The 20-Hz excitation corresponds to the first-mode deformation of the 83-in. spans which vibrated simultaneously in both the horizontal and vertical direction. The horizontal amplitudes were observed to be larger. There also was some difference between the vibration amplitudes of the top and bottom tubes.
16. On the 89-in. overhanging U-bend, the 20-Hz excitation resulted in a second-mode-type horizontal deformation, characterized by a node about 30 in. from the U-bend end.
17. Test not repeated without slotted restraint because vibrating tubes did not touch.
18. Tubes wedged with shims to eliminate clearance in support holes in TSA nearest U-bend end.
19. All four TSA's purposely misaligned.

APPENDIX E

Physical Properties and Geometric Details

FIGURE E-1
HOLE IN THE END SUPPORT PLATE AT TOP

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E-1

$$\begin{aligned}\frac{y}{x} &= \tan 30^\circ \\ x &= 13.5'' \\ y &= x \tan 30^\circ \\ \tan 30^\circ &= 0.57735 \\ y &= 7.794''\end{aligned}$$

$$A_{ESP_T} = (46.875)(19.0) - (13.5)^2 (\tan 30^\circ) =$$

$$A_{ESP_T} = (46.875)(19) - (13.5)(7.794) = 785.4 \text{ in}^2 = 5.454 \text{ ft}^2$$

This is total area of the hole in ESP.

FIGURE E-2

TUBE SPACING GEOMETRY EQUILATERAL TRIANGLE SPACING

~~11/11~~ - 3/16" HOLES IN ~~11~~ SUPPORT PLATES 8-9, 8-1, 8-2 E-3

(Avg 206168, "SG Bundle Details")

("Detail C")

+
("Plan View Bundle")

$$A_{3/16} = \frac{\pi}{4} \left(\frac{3}{16} \right)^2 = 0.27612 \text{ in}^2$$

SUPPORT PLATE	No. of 3/16" Holes	Total area of 3/16" Holes
ESP - 8-9	4308	118.95 in ²
SP - 8-1	3556	98.19 in ²
SP - 8-2	3556	98.19 in ²

PLATE-TO-
SHROUD
CRESCENCE

TABLE E-I

(36)

CHARACTERISTICS OF TUBING

O.D. of Tubing	B.W.G. Gauge	Thick-ness Inches	Internal Area Sq. Inch	Sq. Ft. External Surface Per Foot Length	Sq. Ft. Internal Surface Per Foot Length	Weight Per Ft. Length Steel Lbs.*	I. D. Tubing Inches	Moment of Inertia Inches ⁴	Section Modulus Inches ³	Radius of Gyration Inches	Constant C ¹	O. D. I. D.	Metal Area (Transverse Metal Area) Sq. Inch
1/4	22	.028	.0295	.0655	.0508	.066	.194	.00012	.00098	.0792	46	1.289	.0195
1/4	24	.022	.0333	.0655	.0539	.054	.206	.00011	.00083	.0810	52	1.214	.0159
1/4	26	.018	.0360	.0655	.0560	.045	.214	.00009	.00071	.0824	56	1.168	.0131
3/8	18	.049	.0603	.0982	.0725	.171	.277	.00068	.0036	.1164	94	1.354	.0502
3/8	20	.035	.0731	.0982	.0798	.127	.305	.00055	.0029	.1213	114	1.233	.0374
3/8	22	.028	.0799	.0982	.0835	.104	.319	.00046	.0025	.1227	125	1.176	.0305
3/8	24	.022	.0860	.0982	.0867	.083	.331	.00038	.0020	.1248	134	1.133	.0244
1/2	16	.065	.1075	.1309	.0969	.302	.370	.0022	.0086	.1556	168	1.351	.0888
1/2	18	.049	.1269	.1309	.1052	.236	.402	.0018	.0072	.1606	198	1.244	.0694
1/2	20	.035	.1452	.1309	.1126	.174	.430	.0014	.0056	.1649	227	1.163	.0511
1/2	22	.028	.1548	.1309	.1162	.141	.444	.0012	.0046	.1671	241	1.126	.0415
5/8	12	.109	.1301	.1636	.1066	.602	.407	.0061	.0197	.1864	203	1.536	.177
5/8	13	.095	.1486	.1636	.1139	.537	.435	.0057	.0183	.1903	232	1.437	.158
5/8	14	.083	.1655	.1636	.1202	.479	.459	.0053	.0170	.1938	258	1.362	.141
5/8	15	.072	.1817	.1636	.1259	.425	.481	.0049	.0156	.1971	283	1.299	.125
5/8	16	.065	.1924	.1636	.1296	.388	.495	.0045	.0145	.1993	300	1.263	.114
5/8	17	.058	.2035	.1636	.1333	.350	.509	.0042	.0134	.2016	317	1.228	.103
5/8	18	.049	.2181	.1636	.1380	.303	.527	.0037	.0118	.2043	340	1.186	.089
5/8	19	.042	.2298	.1636	.1416	.262	.541	.0033	.0105	.2068	358	1.155	.077
5/8	20	.035	.2419	.1636	.1453	.221	.555	.0028	.0091	.2089	377	1.126	.065
3/4	10	.134	.1825	.1963	.1262	.884	.482	.0129	.0344	.2229	285	1.556	.260
3/4	11	.120	.2043	.1963	.1335	.809	.510	.0122	.0326	.2267	319	1.471	.238
3/4	12	.109	.2223	.1963	.1393	.748	.532	.0116	.0309	.2299	347	1.400	.220
3/4	13	.095	.2463	.1963	.1466	.666	.560	.0107	.0285	.2340	384	1.399	.196
3/4	14	.083	.2679	.1963	.1529	.592	.584	.0098	.0262	.2376	418	1.284	.174
3/4	15	.072	.2884	.1963	.1587	.520	.606	.0089	.0238	.2410	450	1.238	.153
3/4	16	.065	.3019	.1963	.1623	.476	.620	.0083	.0221	.2433	471	1.210	.140
3/4	17	.058	.3157	.1963	.1660	.428	.634	.0076	.0203	.2455	492	1.183	.126
3/4	18	.049	.3339	.1963	.1707	.367	.652	.0067	.0178	.2484	521	1.150	.108
3/4	20	.035	.3632	.1963	.1780	.269	.680	.0050	.0134	.2532	567	1.103	.079
7/8	10	.134	.2892	.2291	.1589	1.061	.607	.0221	.0505	.2662	451	1.481	.312
7/8	11	.120	.3166	.2291	.1662	.969	.635	.0208	.0475	.2703	494	1.378	.285
7/8	12	.109	.3390	.2291	.1720	.891	.657	.0196	.0449	.2736	529	1.332	.267
7/8	13	.095	.3685	.2291	.1793	.792	.685	.0180	.0411	.2778	575	1.277	.233
7/8	14	.083	.3948	.2291	.1856	.704	.709	.0164	.0374	.2815	616	1.234	.207
7/8	16	.065	.4359	.2291	.1950	.561	.745	.0137	.0312	.2873	680	1.174	.165
7/8	18	.049	.4742	.2291	.2034	.452	.777	.0109	.0249	.2925	740	1.126	.127
7/8	20	.035	.5090	.2291	.2107	.313	.805	.0082	.0187	.2972	794	1.087	.092
1	8	.165	.3526	.2618	.1754	1.462	.670	.0392	.0784	.3009	550	1.493	.430
1	10	.134	.4208	.2618	.1916	1.237	.732	.0350	.0700	.3098	656	1.366	.364
1	11	.120	.4536	.2618	.1990	1.129	.760	.0327	.0654	.3140	709	1.316	.332
1	12	.109	.4803	.2618	.2047	1.037	.782	.0307	.0615	.3174	748	1.279	.305
1	13	.095	.5153	.2618	.2121	.918	.810	.0280	.0559	.3217	804	1.235	.270
1	14	.083	.5463	.2618	.2183	.813	.834	.0253	.0507	.3255	852	1.199	.239
1	15	.072	.5755	.2618	.2241	.714	.856	.0227	.0455	.3291	898	1.167	.210
1	16	.065	.5945	.2618	.2278	.649	.870	.0210	.0419	.3314	927	1.149	.191
1	18	.049	.6390	.2618	.2361	.496	.902	.0166	.0332	.3366	997	1.109	.146
1	20	.035	.6793	.2618	.2435	.360	.930	.0124	.0247	.3414	1060	1.075	.106
1-1/4	7	.180	.6221	.3272	.2330	2.057	.890	.0890	.1425	.3836	970	1.404	.605
1-1/4	8	.165	.6648	.3272	.2409	1.921	.920	.0847	.1355	.3880	1037	1.359	.565
1-1/4	10	.134	.7574	.3272	.2571	1.598	.982	.0741	.1186	.3974	1182	1.273	.470
1-1/4	11	.120	.8012	.3272	.2644	1.448	1.010	.0688	.1100	.4018	1250	1.238	.426
1-1/4	12	.109	.8365	.3272	.2702	1.329	1.032	.0642	.1027	.4052	1305	1.211	.391
1-1/4	13	.095	.8825	.3272	.2775	1.173	1.060	.0579	.0926	.4097	1377	1.179	.345
1-1/4	14	.083	.9229	.3272	.2838	1.033	1.084	.0521	.0833	.4136	1440	1.153	.304
1-1/4	16	.065	.9852	.3272	.2932	.823	1.120	.0426	.0682	.4196	1537	1.116	.242
1-1/4	18	.049	1.042	.3272	.3016	.629	1.152	.0334	.0534	.4250	1626	1.085	.185
1-1/4	20	.035	1.094	.3272	.3089	.456	1.180	.0247	.0395	.4297	1707	1.059	.134
1-1/2	10	.134	1.192	.3927	.3225	1.955	1.232	.1354	.1806	.4853	1860	1.218	.575
1-1/2	12	.109	1.291	.3927	.3356	1.618	1.282	.1159	.1546	.4933	2014	1.170	.476
1-1/2	14	.083	1.398	.3927	.3492	1.258	1.334	.0931	.1241	.5018	2181	1.124	.370
1-1/2	16	.065	1.474	.3927	.3587	.996	1.370	.0756	.1008	.5079	2299	1.095	.293
2	11	.120	2.433	.5236	.4608	2.410	1.760	.3144	.3144	.6660	3795	1.136	.709
2	13	.095	2.573	.5236	.4739	1.934	1.810	.2586	.2586	.6744	4014	1.105	.569
2-1/2	9	.148	3.815	.6540	.5770	3.719	2.204	.7592	.6074	.8332	5951	1.134	1.094

*Weights are based on low carbon steel with a density of 0.2833#/inch³. For other metals multiply by the following factors:

Aluminum	0.35	Nickel-Chrome-Iron	1.07
A.I.S.I. 400 Series Stainless Steels	0.99	Admiralty	1.09
A.I.S.I. 300 Series Stainless Steels	1.02	Nickel and Nickel-Copper	1.13
Aluminum Bronze	1.04	Copper and Cupro-Nickels	1.14
Aluminum Brass	1.06		

**Liquid Velocity = $\frac{\text{Lbs. Per Tube Per Hour}}{C \times \text{SP. GR. of Liquid}}$ in feet per sec. (Sp. Gr. of Water at 60°F. = 1.0)

Inconel-600 properties at $\bar{T}_c = 576^\circ\text{F} (30^\circ)$

$$E = 29.4 \times 10^6 \text{ psi}$$

$$\rho = 518.5 \frac{\text{lbm}}{\text{ft}^3}$$

APPENDIX F

U-Tube Bend Region

The U-tube bend region was considered ^{to be} a critical location for flow-induced vibration, due to its combinations of maximum flow velocities, long unsupported spans of tubing, and the curved shape of the tubes, which decreases the out-of-plane natural frequencies.

The bend region ^{therefore} was studied in more detail, using a SAP IV computer model for the structural response of two selected U-tube bends:

- (a) the maximum-diameter (49.5") bend at the outer edge of the bundle; and
- (b) the maximum-diameter (36") bend which had access to the hole in the End Support Plate (i.e., maximum total tube length combined with high gap flow velocity).

The flow velocities past the U-bends used for these models, were calculated by the method of Singh ⁽²⁴⁾, and are summarized here.

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F-2

(24) NOMENCLATURE for Singh's Method of Calculating Flow Velocities in U-Bend Region

$$X = \frac{R}{r_s} = 3.120$$

$$\rho = (1 - X^{-2})^{1/2} = 0.9472$$

$$\omega = \frac{\psi_2}{\psi_1} = 10.90$$

$$N = 32 = \text{No. of Tube Rows at symmetry midplane } (x=0)$$

$$Z = \frac{x}{R} = \text{variable}$$

$$Q = \dot{m}v = 35.04 \text{ ft}^3/\text{sec}$$

$$V^* = 4.632 \text{ ft/sec}$$

$$\eta = \frac{P-d}{P} = 0.3333$$

$$\alpha = \sin^{-1} \rho = 1.2445 \text{ radians} = 71.3046^\circ \rightarrow 0.5 \sin 2\alpha = -0.303624$$

$$\xi = \frac{R_s}{R} = \frac{25.375}{24.75} = 1.02525$$

$$R = 24.75''$$

- Bundle const. for fixed Q

(24) Singh, K.P., "Predicting Flow-Induced Vibration in U-Bend Regions of Heat Exchangers: An Engineering Solution," Journal of the Franklin Institute, Vol. 302, No. 2, August 1976, pp. 195-205.

$$\omega = \frac{r_s}{r_i} = 10.90$$

$$\chi = \left(\frac{R}{r_s} \right) = \frac{24.75}{7.933} = 3.120$$

$$Z = \left(\frac{x}{R} \right) = \text{variable, space dimension, height of layer}$$

$$\rho = (1 - \chi^{-2})^{1/2} = (1 - (3.120)^{-2})^{1/2} = 0.9472$$

$$N = (\text{No. of tube rows at } x=0), N = 32$$

$$I = \int_0^{\rho} \left[\chi^2 + \frac{\omega \chi (N-1)}{\chi-1} \left\{ \chi - (1 - Z^2)^{1/2} \right\} + \frac{\omega}{2} \left\{ \chi^2 + (1 - Z^2)^{1/2} \right\} \right] dz$$

$$\eta = \frac{p-d}{p} = \frac{0.750 - 0.500}{0.750} = 0.3333$$

$$\xi = \frac{R_s}{R} = \frac{25.375}{24.75} = 1.02525$$

$$\alpha = \sin^{-1} \rho = 71.3053^\circ = 1.2445 \text{ radians}$$

$$R_s = \text{Inside-Shell Radius} = \frac{50.75}{2} = 25.375''$$

$$R = \frac{49.50}{2} = 24.75''$$

$$r_s = \text{Equivalent half-width of baffle window equal in area to existing window}$$

$$r_s = 7.933''$$

$$4 r_s R = A_{\text{window}} = 5.454 \text{ ft}^2$$

$$r_s = \frac{(5.454)(12)}{(4)(24.75)} = 0.6611 \text{ ft} = 7.933''$$

5.454
ft²

1. Volumetric Flow at Top of Bundle, Q

$$\text{Total } Q = \frac{\dot{m}}{\rho} = \frac{\rho A V}{\rho} = A V$$

Unstable -
(b)Stable -
(a)

$$122 < \dot{m} < 183 \text{ lbm/sec.}$$

$$50\% > X_{TOP} > 33\%$$

$$(a) \dot{m} = 183, X = 0.333$$

P = System Pressure = 850 psia

V at top of Bundle for 850 psia

$$V = V_f + X V_{fg} = .02105 + (0.333)(0.51197) = 0.1915 \text{ ft}^3/\text{lbm}$$

$$Q_{TOP} = \text{Total } Q = \frac{\dot{m}}{\rho} = \dot{m} V = (183)(0.1915) = 35.04 \text{ ft}^3/\text{sec}$$

$$(b) \dot{m} = 122, X = 0.50 \rightarrow V = .02105 + .5(0.51197) = .277$$

$$Q_T = (122)(.277) = 33.80$$

2. Number of Tube Rows at midplane of symmetry, N (X=0):

$$N = 63 \text{ rows at midplane of symmetry.}$$

3. I

$$I = \int_0^R \left[\chi^2 + \frac{\omega \chi (N-1)}{\chi-1} \left\{ \chi - (1-z^2)^{-1/2} \right\} + \frac{\omega}{2} \left\{ \chi^2 + (1-z^2)^{-1/2} \right\} \right]^{-1/2} dz$$

$$r_s = \text{waffle slot half-radius} = 7.933''$$

$$R = \text{maximum radius of tube bundle} = \frac{1}{2}(49.5) = 24.75 \text{ inches}$$

$$\chi = \frac{R}{r_s} = \frac{24.75}{7.933} =$$

4. Pressure-Drop Coefficients, ψ_1 , ψ_2 , $\omega = \frac{\psi_2}{\psi_1}$

$\psi_1 = \Delta P$ -coefficient of baffle window (radius r_s)

$\psi_2 = \Delta P$ -coefficient of n tube rows for momentum (pressure drag) and skin friction.

$$\omega = \left(\frac{\psi_2}{\psi_1} \right)$$

$$\Delta P = \frac{\gamma}{2g} \left[\psi_1 V_1^2 + \psi_2 \sum_{i=1}^n V_i^2 \right] \quad (25)$$

Also, Kays and London define ΔP for flow normal to tube banks as

$$\Delta P = \frac{G^2}{2gc} V_1 \left[\underbrace{\left(1 + \sigma^2\right) \left(\frac{V_2}{V_1} - 1\right)}_{\text{static acceleration}} + \underbrace{f_m \left(\frac{A}{A_c}\right) \frac{V_m}{V_1}}_{\text{friction and pressure drag}} \right]$$

or, $\psi_1 = (K_{\text{entrance}} + K_{\text{exit}})$ and $\psi_2 = f_m \left(\frac{A}{A_c}\right) \frac{V_m}{V_1}$

(25) Kays, W.M., and London, A.L., Compact Heat Exchangers, p. 21, McGraw-Hill, N.Y., 1955.

ψ_1 = Baffle Window Loss Coefficient (End Support Plate)
(Equivalent Orifice)

$$\psi_1 = 1.34^{(37)}$$

$$\frac{A_{esp}}{A_1} = \frac{5.454}{14.05} = 0.3882$$

$$A_{esp} = 5.454 \text{ ft}^2$$

$$A_1 = \frac{\pi/4 (50.75)^2}{144} = 14.05 \text{ ft}^2$$

- (37) Spitzglass, J.M., "Orifice Coefficients - Data and Results of Tests,"
ASME Transactions, Vol. 44, 1922, pp. 919-974. (p. 950, Table II)

$$\psi_2 = f_m \left(\frac{A}{A_c} \right) \left(\frac{v_m}{v_i} \right) = \Delta P \text{ coefficient of } n \text{ tube rows, for skin friction and pressure drag}$$

For an ^{equilateral} triangular matrix as shown

$$.06 < f_m < .08 \text{ over a large } Re \text{ range}$$

This tube matrix is not the LOFT SG matrix; however the P/D ratio is the same $\left(\frac{0.5625}{0.500} = 1.5 = \frac{.5625}{.375} \right)$.

This is Figure No. 48 in Kaye and London (page 91)

$$\left. \begin{aligned} \alpha &= \frac{A}{V} = 53.6 \text{ ft}^2/\text{ft}^3 \\ \sigma &= \frac{A_c}{A_{fr}} = 0.366 \end{aligned} \right\} \text{ for the Kaye \& London array above}$$

$$\psi_2 = f_m \left(\frac{A}{A_c} \right) \left(\frac{v_m}{v_i} \right)$$

A = ht. transfer area

V = total free volume

A_c = minimum free flow area

A_{fr} = frontal area

$$\left(\frac{A}{A_c} \right) = \frac{\left(\frac{A}{V} \right)}{\left(\frac{A_c}{A_{fr}} \right)} * \left(\frac{V}{A_{fr}} \right) = \left(\frac{\alpha}{\sigma} \right) \left(\frac{V}{A_{fr}} \right)$$

$V = V_h = \text{hemisphere volume} - \text{tube volume} = V_h - V_{\text{tubes bands}}$

$$V_h = \frac{1}{2} \left[\frac{4}{3} \pi R^3 \right] = \frac{1}{2} \left[\left(\frac{4}{3} \pi \right) \left(\frac{24.75}{12} \right)^3 \right] = 18.38 \text{ ft}^3$$

$$V_{\text{tubes bands}} = \sum_{i=1}^N \pi n R_i^2 \left(\frac{\pi_4 (0.5)^2}{1728} \right) = \sum_{i=1}^N \frac{\pi^2 (0.25) n R_i^2}{1728} = \sum_{i=1}^N \frac{0.669 n R_i^2}{1744 \cdot 12} = 3.574 \sum_{i=1}^N R_i^2 \text{ (ft}^3\text{)}$$

i = row no.
 n = no. of bands in row

LTR 1141-30

$$V_{\text{tubes bends}} = (3.57-4) \sum_{i=1}^N n R_i'' \quad (11^3) = \left(\frac{3.57-4}{1} \right) \sum_{i=1}^N D_i''$$

$$V_{\text{tubes bends}} = 1.785-4 \sum_{i=1}^N D_i'' = 7.409 \text{ ft}^3$$

row = i	no. of bends in each row = n	D_i''	$n D_i''$	$\sum_{i=1}^N n D_i''$	$V_{\text{tubes bends}} (11^3) = 1.785-4 \sum_{i=1}^N D_i''$
1	37	3"	111"	111"	
2	38	3.75"			
3	37	4.5			
4	38	5.25			
5	37	6			
6	38	6.75			
7	37	7.5			
8	38	8.25			
9	37	9			
10	38	9.75			
11	37	10.5			
12	38	11.25			
13	37	12			
14	36	12.75			
15	37	13.5			
16	36	14.25			
17	37	15			
18	36	15.75			
19	37	16.5			
20	36	17.25			
21	35	18			
22	36	18.75			
23	35	19.5			
24	34	20.25			
25	35	21			
26	34	21.75			
27	33	22.5			
28	34	23.25			
29	33	24			
30	34	24.75			
31	33	25.5			
32	32	26.25			
33	33	27			
34	32	27.75			
35	31	28.5			
36	30	29.25			
37	31	30			
38	30	30.75			
39	29	31.5			

LTR 1141-30

7-9

i	n	D_i	$n D_i$	Σ	Tube bands (11 ³) = 1.715, Σ
40	28	32.25"			
41	29	33			
42	28	33.75			
43	27	34.5			
44	26	35.25			
45	27	36			
46	26	36.75			
47	25	37.5			
48	24	38.25			
49	23	39			
50	22	39.75			
51	21	40.5			
52	22	41.25			
53	21	42			
54	20	42.75			
55	19	43.5			
56	18	44.25			
57	17	45			
58	14	45.75			
59	13	46.5			
60	12	47.25			
61	9	48			
62	6	48.75			
63	2	49.5			

41508.

7.409 ft 3

$$V = V_h - V_{\text{tube bundle}} = 18.38 - 7.41 = 10.97 \text{ ft}^3 \text{ free volume}$$

$$A_{fr} = \frac{2\pi R_m^2}{2} = 2\pi R_m^2$$

$$R_m = \frac{1}{2} \left(1.5 + \frac{50.125}{2} \right) = 13.281 \text{ inches}$$

$$A_{fr} = 2\pi R_m^2 = 2\pi \left(\frac{13.281}{12 \text{ inches/ft}} \right)^2 = 7.6962 \text{ ft}^2$$

$$\left(\frac{V}{A_{fr}} \right) = \left(\frac{10.97 \text{ ft}^3}{7.6962 \text{ ft}^2} \right) = 1.425 \text{ ft}^3/\text{ft}^2$$

$$\therefore \left(\frac{A}{A_c} \right) = \left(\frac{\alpha}{\sigma} \right) \left(\frac{V}{A_{fr}} \right) = \left(\frac{53.6}{0.366} \right) (1.425) = 208.7$$

$$\psi_2 = f_m \left(\frac{A}{A_c} \right) \left(\frac{V_m}{V_1} \right) = (0.07) (208.7) = 14.61$$

$$\omega = \frac{\psi_2}{\psi_1} = \frac{14.61}{1.34} = 10.90$$

$$\rho = 0.9472$$

$$\chi = 3.120$$

$$\omega = 10.90$$

$$N = 32$$

Constants

$$I = \int_0^{\rho} \left[\chi^2 + \left[\frac{\omega \chi (N-1)}{\chi-1} \right] \left\{ \chi - (1-z^2)^{-1/2} \right\} + \frac{\omega}{2} \left\{ \chi^2 + (1-z^2)^{-1} \right\} \right]^{-1/2} dz$$

$$z = 0 + n \Delta z - \frac{1}{2} \Delta z = (n-1) \Delta z + \frac{1}{2} \Delta z = (n-1/2) \Delta z, n=1,2,\dots$$

$$\chi^2 = (3.120)^2 = 9.734$$

$$\left[\frac{\omega \chi (N-1)}{\chi-1} \right] = \frac{(10.90)(3.120)(32-1)}{(3.120-1)} = 497.29$$

$$\frac{\omega}{2} = \frac{10.90}{2} = 5.45$$

$$I = \int_0^{\rho} \left[9.734 + 497.29 \left\{ \overset{3.120}{\chi} - (1-z^2)^{-1/2} \right\} + 5.45 \left\{ 9.734 + (1-z^2)^{-1} \right\} \right]^{-1/2} dz$$

$$I = \int_0^{\rho} \left[9.734 + 1551.53 - 497.29 (1-z^2)^{-1/2} + 53.05 + 5.45 (1-z^2)^{-1} \right]^{-1/2} dz$$

$$I = \sum_0^{\rho} \left[\overset{A}{1614.32} - \overset{B}{497.29} (1-z^2)^{-1/2} + \overset{C}{5.45} (1-z^2)^{-1} \right]^{-1/2} \Delta z$$

$$z = (n-1/2) \Delta z, n=1,2,3,\dots$$

$$n = \frac{\rho}{\Delta z}$$

$$I = .031170421 \sim .03117, \text{ for } \Delta z = .005$$

$$(34) \quad Q = 2\pi R^2 V^* \left[0.5\eta \{ \alpha + 0.5 \sin 2\alpha \} + \frac{1}{\chi} \left\{ \epsilon - (1 - \chi^2)^{1/2} \right\} \right], \text{ defines } V^*$$

$$(24) \quad V(y, r) = \frac{C}{\pi r \left[\frac{1}{r_s^2} + \frac{\omega \chi (N-1)}{(1-\chi)R} \left(\frac{1}{r_s} - \frac{1}{y} \right) + \frac{\omega}{2} \left(\frac{1}{r_s^2} + \frac{1}{y^2} \right) \right]^{1/2}}$$

find C from (21)

$$Q = 2CR^2 \left[\frac{\{ \epsilon - (1 - \chi^2)^{1/2} \}}{\chi (1 + \omega)^{1/2}} + \eta I \right]$$

Find C

LTR 141-30

$$\omega = 10.90$$

$$Q = 2CR^2 \left[\frac{\left\{ \xi - (1 - \bar{\kappa}^2)^{1/2} \right\}}{\bar{\kappa}(1 + \omega)^{1/2}} + \eta I \right] = 2CR^2 []$$

$$C = \frac{Q}{2R^2 []} [=] \frac{(\text{ft}^3/\text{sec})}{(\text{ft}^2)} [=] \left(\frac{\text{ft}}{\text{sec}} \right)$$

$$[] = \left[\frac{\left\{ 1.02525 - (1 - (3.120)^{-2})^{1/2} \right\}}{(3.120)(1 + 10.90)^{1/2}} + (0.3333)(0.3117) \right]$$

$$[] = .017637$$

$$C = \frac{35.04}{(2) \left(\frac{24.75}{12} \right)^2 [.017637]} = 233.52 \left(\frac{\text{ft}}{\text{sec}} \right)$$

Find $\check{V}^*$

LTR 1141-30

$$\check{Q} = 35.04 \text{ ft}^3/\text{sec}$$

$$\check{\eta} = \frac{P-d}{P} = 0.3333$$

$$\check{\alpha} = \sin^{-1} \rho = 1.2445 \text{ radians} \xrightarrow{71.304^\circ} 0.5 \sin 2\alpha = 0.303624$$

$$\check{R} = \frac{R}{r_s} = 3.120 \quad r_s = 7.9328''$$

$$\check{\xi} = \frac{R_s}{R} = \frac{25.375}{24.75} = 1.02525$$

$$\check{\omega} = 10.90 = \frac{2\pi}{T}$$

$$\check{R} = 24.75'' \quad N = 32$$

$$\check{Q} = 2\pi \check{R}^2 \check{V}^* \left[0.5 \check{\eta} \left\{ \check{\alpha} + 0.5 \sin 2\alpha \right\} + \frac{1}{\check{R}} \left\{ \check{\xi} - (1 - \check{R}^{-2})^{1/2} \right\} \right] = 2\pi \check{R}^2 \check{V}^* [] = \check{Q}$$

$$\check{V}^* = \frac{\check{Q}}{2\pi \check{R}^2 []} \quad \left(\frac{\text{ft}^3}{\text{sec}} \right)$$

$$[] = \left[(0.5)(0.3333) \left\{ 1.2445 + 0.303624 \right\} + \left(\frac{1}{3.120} \right) \left\{ 1.02525 - (1 - (3.120)^{-2})^{1/2} \right\} \right]$$

$$[] = 0.2830$$

$$\check{V}^* = \frac{35.04 \text{ (ft}^3/\text{sec)}}{(2\pi) \left(\frac{24.75}{12} \right)^2 [0.2830]} = 4.632 \text{ ft/sec}$$

Find $V(y, r)$

LTR 1141-30

$$V(y, r) = \frac{c}{\pi r \left[\left(\frac{1}{r_s^2} \right) + \left(\frac{\omega \chi (N-1)}{(\chi-1) R''} \right) \left(\frac{1}{r_s} - \frac{1}{y} \right) + \frac{\omega}{2} \left(\frac{1}{r_s^2} + \frac{1}{y^2} \right) \right]^{1/2}}$$

$$\left(\frac{\omega \chi (N-1)}{(\chi-1) R''} \right) = \left(\frac{(10.90)(3.120)(32-1)}{(3.120-1) \left(\frac{27.45}{12} \right)} \right)$$

$$\left(\frac{\omega \chi (N-1)}{(\chi-1) R''} \right) = (217.39) \left(\frac{1}{ft} \right)$$

$$\left(\frac{1}{r_s^2} \right) = \frac{1}{\left(\frac{7.933}{12} \right)^2} = 2.288 \left(\frac{1}{ft^2} \right)$$

$$\left(\frac{1}{r_s} - \frac{1}{y} \right) = \left(\frac{1}{\left(\frac{7.933}{12} \right)} - \frac{1}{\left(\frac{y}{12} \right)} \right) = \left(1.5127 - \frac{12}{y} \right)$$

$$\left(\frac{\omega}{2} \right) \left(\frac{1}{r_s^2} + \frac{1}{y^2} \right) = \left(\frac{10.90}{2} \right) \left(2.288 + \frac{144}{y^2} \right) = \left(12.47 + \frac{784.8}{y^2} \right)$$

$$\left(\frac{c}{\pi r} \right) = \left(\frac{c}{(\pi) \frac{r''}{12}} \right) = \left(\frac{(12)c}{(\pi)r''} \right) = \frac{(12)(233.52)}{(\pi)r''} = \frac{891.98}{r''}$$

$$\left(\frac{c}{\pi r} \right) = \left(\frac{891.98}{r''} \right)$$

Find $V(y, r)$

LTR 1141-30

F-16

$$V(y, r) = \frac{C}{\pi r \left[\left(\frac{1}{r_s^2} \right) + \left(\frac{\omega \lambda (N-1)}{(X-1)R} \right) \left(\frac{1}{r_s} - \frac{1}{y} \right) + \left(\frac{\omega}{2} \right) \left(\frac{1}{r_s^2} + \frac{1}{y^2} \right) \right]^{1/2}}$$

$$V(y, r) = \frac{891.98}{r'' \left[2.288 + (217.39) \left(\frac{1.5127}{y} \right) + \left(12.47 + \frac{784.8}{y^2} \right) \right]^{1/2}}$$

$$V(y, r) = \frac{891.98}{r'' \left[2.288 + 328.85 - \frac{2608.68}{y''} + 12.47 + \frac{784.8}{y''^2} \right]^{1/2}}$$

$$V(y, r) = \frac{891.98}{r'' \left[343.61 - \frac{2608.68}{y''} + \frac{784.8}{y''^2} \right]^{1/2}}$$

The resulting velocity expression is

$$V(y, r) = \frac{A}{r'' \left[B + \left(\frac{C}{y''} \right) + \frac{D}{y''^2} \right]^{1/2}}$$

$$A = 891.98$$

$$B = 343.61$$

$$C = -2608.68$$

$$D = 784.8$$

$(y \text{ must be } \geq 7.9328'')$

$$y \geq 7.9328''$$

$$\frac{12}{y} \leq 1.5127$$

$$\left(1.5127 - \frac{12}{y} \right) = \left(\frac{1.5127 - 12}{7.9328} \right)$$

$$- \frac{2608.68}{7.9328} = -328.85$$

APPENDIX G

SAP-IV Models for Vibration Response of U-Tubes in the
Bend Region of the LOFT Steam Generator

Two U-tube ^{sections} in the bend regions of the LOFT Steam Generator were selected for modeling on the SAP-IV structural analysis program. These two models were structural cases 17 and 18, representing the 49.5²-inch diameter and 36^{-inch} diameter U-bends respectively. The 49.5^{-inch} diameter bend was selected because it is the largest U-bend in the tube bundle, and the 36-inch bend was the largest U-bend which had access to the hole in the End Support Plate, thereby maximizing the tube unsupported length and combining that with a higher ~~flow~~ ^{steam} flow velocity than that seen by the 49.5-inch bend.

It is possible that some other bend region could have a more critical combination of low natural frequency and high imposed fluid force, but these two cases are considered likely worst cases. The forcing frequency is close to their second-mode natural frequencies, whereas a smaller bend diameter would result in a mismatch of forcing frequency and natural frequency.

The turbulent - buffeting load was greater than the von Karman vortex load, ~~the~~ and the tube natural frequency was ~~about~~ approximately as close a match to the turbulence frequency as to the vortex frequency, therefore the turbulent - buffeting forcing function was used. (This also was the case for Case 18.)

The damping ratio was taken as the value .002^{for both Saffman cases}, i.e. the minimum value measured by Halle et al. (23)

The turbulent - buffet load was calculated to be

$$W = C_D q_t \frac{S}{L} = C_D q_t \frac{Ld}{L} = C_D q_t d$$

$$d = 0.5''$$

$$q_t = 0.25 q = \frac{0.25 V^2}{2g_c \nu} = \frac{0.25 (.503)^2 (4.632)^2}{(288)(32.17)(.1915)}$$

$$q_t = .0007648 \text{ psi}$$

$$W = (1.2)(.0007648)(0.5) = .000458 \text{ lb/in.}$$

Here, the gas velocity at the U-bend is 0.503 times the average V^* velocity (4.632 ft/sec) for the bundle, given in Figure 3. The outlet specific volume, 0.1915 ft³/lbm, is used (for $m = 183 \text{ lbm/sec}$, which gives highest dynamic velocity head).

Case 17 - U-Tube SAP Model for $D=49.5''$
 SAP Model - Turbulent Buffeting on U-Tube ($49.5'' \text{ D}$)

B-2

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✓ $\beta = .002$

✓ $f_z = 41.3 \text{ cps (turb.)}$

✓ $W = .00046 \text{ lb}_f/\text{in}$

✓ $I' = .002342 \text{ in}^4$ ($f_{n2} = 39.2 \text{ cps}$)

(corrected for pressurization)

Note: This load is actually applied at 90° to the direction shown (out-of-plane).

$l = \pi/2 (49.5) + 17.25 = 77.25 + 17.25 = 94.5''$

$N = \frac{94.5}{5} = 19 \text{ legs}$

$S = 5'' \text{ each}$

Time Step:

$\frac{1}{10} \text{ of } \left(\frac{1}{40} \text{ sec}\right) = \frac{1}{500} \text{ sec} = .002 \text{ sec}$

$\frac{5000}{10000} \Delta t = \frac{10}{20} \text{ sec}$

Case 17 - U-Tube SAP Model $f_n = 39.2 \text{ cps}$ $D = 49.5''$

6-2A

$$R = \frac{49.5}{2} = 24.75''$$

$$f_t = 41.3 \text{ cps}$$

$$l_1 = \pi/2 D \left(\frac{1}{16} \right) = 4.860''$$

$$f_s =$$

$$l_2 = \frac{17.25}{3} = 5.75''$$

$$16 (4.860) = 77.76''$$

$$\frac{\pi D}{2} = \left(\frac{\pi}{2} \right) (49.5) = 77.75'' \quad \left. \vphantom{\frac{\pi D}{2}} \right\} \text{OK}$$

Node, (N)	X"	Y"
①	24.75	0.
②	24.2744	4.828
③	22.866	9.471
④	20.579	13.750
⑤	17.501	17.501
⑥	13.750	20.579
⑦	9.471	22.866
⑧	4.828	24.274
⑨	0.	24.750
⑩	-4.828	24.274
⑪	-9.471	22.866
⑫	-13.750	20.579
⑬	-17.501	17.501
⑭	-20.579	13.750
⑮	-22.866	9.471
⑯	-24.274	4.828
⑰	-24.75	0.
⑱	-24.75	-5.75

Extra K-node

$$g^* = \left(\frac{g}{R}\right) = 1.0$$

$$r^* = \left(\frac{r}{R}\right) = 1.0$$

$$\left(\frac{V}{V^*}\right) = 0.5028$$

$$V^* = 4.632 \text{ fps}$$

$$V = 2.329 \text{ fps}$$

$$q = \frac{\rho V^2}{2\gamma_c} = \frac{V^2}{2\gamma_c r} = \frac{(2.329)^2}{(288)(32.174)(.1915)} = .00306 \text{ psi}$$

$$q_t \approx 0.25 q = .000764 \text{ psi}$$

a) Karman:

$$\left(\frac{L}{l}\right)_K = \frac{C_L q S}{l} = \frac{C_L q d}{l} = C_L q d = (0.28)(.00306)(.5)$$

$$w_K = \left(\frac{L}{l}\right)_K = .000428 \frac{\text{lb}_f}{\text{in}}$$

b) Turbulent-Buffer:

$$w_t = \left(\frac{L}{l}\right)_t \approx \frac{C_D q_t S}{l} = (1.2)(.000764)(.5) = .000458 \frac{\text{lb}_f}{\text{in}}$$

The Karman and Turbulent-Buffer Mechanisms interfere physically with one another, $\therefore$ need not be considered together.

$\therefore$ Use the Turbulent-Buffer load since it is larger.

$$f_t = 41.3 \text{ cps}$$

$$\tau = \frac{1}{41.3} = .0242 \text{ sec.}$$

$$T = 10 \text{ sec. total}$$

$$N = 20 \text{ points per cycle}$$

$$F = 10^4 \sin \left[2\pi \left(\frac{t}{\tau} \right) \right]$$

N	t (sec)	(t/τ)	F (lb_f)
1	0	0	0
2	.00121	.05	3090.
3	.00242	.1	5878.
4	.00363	.15	8090.
5	.00484	.2	9511.
6	.00605	.25	1.0^4
7	.00726	.3	9511.
8	.00847	.35	8090.
9	.00968	.4	5878.
10	.01089	.45	3090.
11	.01210	.50	0.
12	.01331	.55	-3090.
13	.01452	.6	-5878.
14	.01573	.65	-8090.
15	.01694	.7	-9511.
16	.01815	.75	-1.0^4
17	.01936	.8	-9511.
18	.02057	.85	-8090.
19	.02178	.9	-5878.
20	.02299	.95	-3090.
21	.02420	1.00	0.

Mass Density $\left(\rho = \frac{\text{lb}_f \text{ sec}^2}{\text{in}^4} \right)$

$$F = ma$$

$$F = \rho g_c = W$$

$$\rho = \frac{W}{g_c} = \frac{\text{lb}_f \text{ sec}^2}{\text{in}^4} = \left(\frac{\text{lb}_f}{\text{in}^3} \right) \left(\frac{\text{sec}^2}{\text{in}} \right)$$

$$W = \frac{.0337}{A_w} \frac{\text{lb}_f}{\text{in}} \left(\frac{1}{.0694 \text{ in}^2} \right) = 0.4856 \frac{\text{lb}_f}{\text{in}^3}$$

$$\rho = \frac{(0.4856 \frac{\text{lb}_f}{\text{in}^3})}{(12 \frac{\text{in}}{\text{ft}}) (32.174 \frac{\text{ft}}{\text{sec}^2})} = .001258 \frac{\text{lb}_f \text{ sec}^2}{\text{in}^4}$$

$$f_n = 39.2 \text{ cps (2nd Mode)}$$

$$\omega_n = 2\pi f_n = 2\pi(39.2) = 246.3 \text{ rad/sec}$$

$$S = \frac{\pi(49.5)}{4} = 38.88" \sim 38.9"$$

$$K = \frac{P}{\Delta} = \frac{wl}{\Delta} = \frac{wl}{\frac{wl^4}{8EI}} = \frac{8EI}{l^3}$$

$$\Delta = \frac{wl^4}{8EI}$$

$$K = \frac{8EI}{l^3}$$

$$K = \frac{(8)(29.4 \times 10^6)(.002342)}{(38.9)^3} \text{ (lb/in)} = 9.358 \text{ lb/in} \sim 9.36 \text{ lb/in}$$

$$K = 9.358 \text{ lb/in} \sim 9.36 \text{ lb/in}$$

$$C_c = 2M\omega_n$$

$$M = ml = (.0337 \text{ lbm/in})(38.9) \text{ in} = 1.311 \text{ lbm}$$

$$C_c = 2M\omega_n = 2(1.311 \text{ lbm})(246.3 \text{ rad/sec}) = 645.8 \frac{\text{lbm rad}}{\text{sec}}$$

$$C_c = (645.8 \frac{\text{lbm rad}}{\text{sec}}) \left(\frac{1 \text{ ft}}{12 \text{ in}} \right) \left(\frac{1 \text{ sec}^2}{32.17 \text{ lbm ft}} \right) = 1.673 \frac{\text{lb sec}}{\text{in}}$$

$$\beta K = C = .002 C_c = .00335 \frac{\text{lb sec}}{\text{in}}$$

$$\beta = C/K = .000357 \text{ sec}$$

Following is the SAP-IV input for Case 18 (the 36-inch U-bend, including a 17.375-inch straight leg to the baffle below the End Support Plate).

The gap velocity in the U-bend region is increased to 3.49 feet per second because of the smaller bend diameter. The load on the straight section is neglected even though the radial velocity at the centerline, mostly because the tube is far removed from the centerline and sees more (parallel) leakage flow than crossflow.

Case 18 - U-Tube SAP Model for $D=36"$

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$D=36"$

6-7

$$f_{n2} = 42.17$$

$$\frac{49.5 - 3}{.75} = \frac{46.5}{.75} = 62.00$$

The largest U-Tube which clears the BP baffle is,

$$D = 3 + N \times 0.75 \geq 2 \times 18'' = 36''$$

(dia. increases by 0.75" from one row to next)

$$\therefore N \geq \frac{(36 - 3)}{0.75} = 44.$$

Or, $D = 36''$.

$$N = 12 \times 6'' + (1.80) = 13$$

$S = \text{element length} = 6''$

$$v = \frac{\dot{m} v}{A} = \frac{(183)(1915)}{5.454} = 6.43 \text{ fps}$$

$$A_{E30} = 5.454 \text{ ft}^2$$

(Find $\max(\frac{V}{V^*})$): (i.e. find y^* which maximizes $(\frac{V}{V^*})$):

$$r = \frac{36}{2} = 18$$

$$R = \frac{49.5''}{2} = 24.75''$$

$$r^* = \left(\frac{r}{R}\right) = \frac{18}{24.75} = 0.7273$$

$$r^* = \left(\frac{r}{R}\right) = \frac{18}{24.75} = 0.7273$$

So, min. possible y^* at this r^* value, is the same as r^* , or $y_{\min}^* = 0.7272$.

The max. value of $f\left(\frac{V}{V_*}\right)$ then is 0.7544

$$V^* = 4.632 \text{ fps}$$

$$V = (0.754)(4.632) = 3.49 \text{ fps}$$

$$q_u = \frac{\rho v^2}{2g_c} = \frac{v^2}{2g_c} = \frac{(3.49)^2}{(288)(32.174)} \frac{\text{ft}^2}{\text{sec}^2} \left(\frac{\text{lbm}}{\text{ft}^3} \right) \left(\frac{\text{ft}}{\text{sec}} \right) \left(\frac{\text{sec}^2}{\text{ft}} \right) (0.1915 \frac{\text{ft}^3}{\text{lbm}})$$

$$q_u = .00686 \text{ psi}$$

$$q_s = \frac{\rho v^2}{2g_c} = \frac{v^2}{2g_c} = \frac{(9.42)^2}{(3.49)^2} (.00686) = .05 \text{ psi}$$

$$\left(\frac{w}{d} \right)_u = \frac{C_L q_u S}{l} = \frac{C_L q_u d \ell}{\ell} = C_L q_u d = (0.28)(.00686)(0.5)$$

$$\left(\frac{w}{d} \right)_u = .000960 \text{ lb}_f/\text{in} \quad \text{max.}$$

$$\left(\frac{w}{d} \right)_s = \frac{C_L q_s S}{l} = C_L q_s d = (0.28)(.05)(.5) = .007 \frac{\text{lb}_f}{\text{in}}$$

18

Y-X-θ

LTR 1141-30

G-11

Node No., N	Run θ = X"	Run θ = Y"	θ°
①	18.000	0.0"	0°
②	17.009"	5.8885"	19.098°
③	14.146	11.1307	
④	9.725	15.146	
⑤	4.234	17.495	
⑥	-1.723	17.917	
⑦	-7.491	16.367	
⑧	-12.434	13.016	
⑨	-16.008	8.231	
⑩	-17.819	2.540	
⑪	-18.000"	-3.460	
⑫	-18.000	-9.46	
⑬	-18.000	-15.46	
⑭	-18.000	-21.46 -17.25

$$S = 6"$$

$$R = 18"$$

$$S = R\theta$$

$$\theta = \frac{S}{R} = \frac{6}{18} = \frac{1}{3} \text{ rad}$$

$$\theta^\circ = 19.09859317^\circ$$

Natural Frequencies

$$f_n = \frac{\lambda_n}{2\pi} \left(\frac{1}{R\theta} \right)^2 \left(\frac{EI}{m} \right)^{1/2}$$

Hz,

$$l = \frac{2\pi R}{2} + 17.25 = 73.8''$$

$$E = 29.4 \times 10^6 \text{ psi}$$

$$I = .001786 \text{ in}^4$$

$$m = .0337 \text{ lbm/in}$$

$$R = 18'' \quad R\theta = (18)(391) = 73.8''$$

$$\theta = 180^\circ + 44^\circ \approx 224^\circ = 391 \text{ rad}$$

$$\lambda_n =$$

$$0.7167 \lambda_n$$

Pressurized

n	λ_n	π	$\left(\frac{\lambda'_n}{\lambda_n} \right)$	$= f_n (\text{Hz})$	$f'_n = \left(\frac{\lambda'_n}{\lambda_n} \right) f_n (\text{Hz})$
1	20	18.42	1.21	14.33	17.34
2	53	$\updownarrow$	1.11	37.99	42.17
3	112		1.06	80.27	85.09
4	188		1.04	134.7	140.1

$$f_n = \frac{\lambda_n}{2\pi} \left(\frac{1}{\cancel{73.8}} \right)^2 \sqrt{\frac{(32.174)(12) \left(\frac{\text{lbm}}{\text{in}^2} \right) (29.4 \times 10^6 \frac{\text{lb}}{\text{in}^2}) (.001786 \text{ in}^4)}{(.0337 \frac{\text{lbm}}{\text{in}})}}$$

$$f_n = 0.7167 \lambda_n (\text{Hz})$$

$$\theta = 180 + 44 = 224^\circ$$

$$\pi = (.003383) l^2$$

$$f_n =$$

(Hz)

2nd-Mode $f_n' = 42.17 \text{ Hz}$

LTR 1141-30

Turbulent - Buffet Frequency = 41.3 Hz

Karman - Vortex Frequency = $St = 0.53 = \frac{f_n D}{V}$

$$f_s = \frac{(0.53)(3.49)}{\left(\frac{0.5}{12}\right)} = 44.4 \text{ Hz}$$

Damping for Cantilevered U-Tube:

$$f_n = \sqrt{\frac{EI}{m}}$$

$$I = \left(\frac{f_n}{2}\right)^2$$

$$I' = I \left(\frac{f_n'}{f_n}\right)^2 = (.001786) \left(\frac{42.17}{37.99}\right)^2 = .002201 \text{ in}^4$$

$$\omega_n = 2\pi f_n' = 265 \frac{\text{rad}}{\text{sec}}$$

$$K = \frac{P}{\Delta} = \frac{wl}{\Delta} = \frac{wl}{\frac{wl^4}{8EI}} = \frac{8EI}{l^3}$$

$$K = \frac{(8)(29.4 \times 10^6 \text{ psi})(.002201 \text{ in}^4)}{(36.9)^3 \text{ in}^3} = 10.30 \frac{\text{lb}_f}{\text{in}}$$

$$M = ml = (.0337)(36.9) = 1.244 \text{ lb}_m$$

$$C_c = 2M\omega_n = 2(1.244)(265) = 659.2 \frac{\text{lb}_m \text{ rad}}{\text{sec}} \times \frac{1}{12} \times \frac{1}{32.174} = 1.707 \frac{\text{lb}_f \text{ sec}}{\text{in}}$$

$$\beta K = C = (.002)(1.707) = .003415 \text{ lb}_f \text{ sec/in}$$

$$\beta = \frac{C}{K} = \frac{.003415}{10.3} = .000332 \text{ lb}_f \text{ sec/in}$$

Scalar Multiplier (SF)

LTR 1141-30 G-14

$$SF = \frac{F(t) \leftarrow \text{result}}{f(t) \leftarrow f_i}$$

$l = \text{element length} = 6''$

$$F(t) = SF * f(t)$$

(W_f)

$$f(t) = 1000. \text{ (max.)}$$

$$F(t) = .00096 \text{ } W_f / \text{in (max.)} * 6 \text{ in.} = .00576 \text{ } W_f$$

per element.
(node)

~~.00096~~

$$.00576 = SF * 1000.$$

$$SF = \frac{.00576}{1000} = 5.76 - 6$$

$$F(t)_{\text{max}} = (5.76 - 6)(1000.) = 5.76 - 3 = .00576 \text{ } W_f$$

max.

The results of the SAP-IV runs are given in Figures 6 and 7. These results show small out-of-plane vibratory motion of the U beads, resulting in fretting wear but no tube-to-tube contact.

CASE 17, U-TUBE

ESP/ESP, DAMP=.002, 49.50, FT=41.3, FN2=39.2HZ

CONTROL INFORMATION

NUMBER OF NODAL POINTS: 18
 NUMBER OF ELEMENT TYPES: 1
 NUMBER OF LOAD CASES: 0
 NUMBER OF FREQUENCIES: 1
 ANALYSIS CODE (NOYN): 4
 EQ.0, STATIC
 EQ.1, MODAL EXTRACTION
 EQ.2, FORCED RESPONSE
 EQ.3, RESPONSE SPECTRUM
 EQ.4, DIRECT INTEGRATION
 SOLUTION MODE (MODFX): 0
 EQ.0, EXECUTION
 EQ.1, DATA CHECK
 NUMBER OF SUBSPACE: 0
 ITERATION VECTORS (INAD): 0
 EQUATIONS PER BLOCK: 0
 TAPE10 SAVE FLAG (N10SV): 0

NODAL POINT INPUT DATA

NODE NUMBER	BOUNDARY	CONDITION	CODES	XX	YY	ZZ
1	1	1	1	0	0	0
2	1	1	1	0	0	0
3	1	1	1	0	0	0
4	1	1	1	0	0	0
5	1	1	1	0	0	0
6	1	1	1	0	0	0
7	1	1	1	0	0	0
8	1	1	1	0	0	0
9	1	1	1	0	0	0
10	1	1	1	0	0	0
11	1	1	1	0	0	0
12	1	1	1	0	0	0
13	1	1	1	0	0	0
14	1	1	1	0	0	0
15	1	1	1	0	0	0
16	1	1	1	0	0	0
17	1	1	1	0	0	0
18	1	1	1	0	0	0

NODAL POINT COORDINATES

NODE	X	Y	Z	T
1	24.750	0.000	0.000	540.000
2	24.274	4.828	0.000	540.000
3	22.866	9.471	0.000	540.000
4	20.579	13.750	0.000	540.000
5	17.501	17.501	0.000	540.000
6	13.750	20.579	0.000	540.000
7	9.471	22.866	0.000	540.000
8	4.828	24.274	0.000	540.000
9	0.000	24.750	0.000	540.000
10	-4.828	24.274	0.000	540.000
11	-9.471	22.866	0.000	540.000
12	-13.750	20.579	0.000	540.000
13	-17.501	17.501	0.000	540.000
14	-20.579	13.750	0.000	540.000
15	-22.866	9.471	0.000	540.000
16	-24.274	4.828	0.000	540.000
17	-24.750	0.000	0.000	540.000
18	-24.750	-7.250	0.000	540.000

GENERATED NODAL DATA

NODE NUMBER	BOUNDARY	CONDITION	CODES	XX	YY	ZZ
1	1	1	1	0	0	0
2	1	1	1	0	0	0
3	1	1	1	0	0	0
4	1	1	1	0	0	0
5	1	1	1	0	0	0
6	1	1	1	0	0	0
7	1	1	1	0	0	0
8	1	1	1	0	0	0
9	1	1	1	0	0	0
10	1	1	1	0	0	0
11	1	1	1	0	0	0
12	1	1	1	0	0	0
13	1	1	1	0	0	0
14	1	1	1	0	0	0
15	1	1	1	0	0	0
16	1	1	1	0	0	0
17	1	1	1	0	0	0
18	1	1	1	0	0	0

NODAL POINT COORDINATES

NODE	X	Y	Z	T
1	24.750	0.000	0.000	540.000
2	24.274	4.828	0.000	540.000
3	22.866	9.471	0.000	540.000
4	20.579	13.750	0.000	540.000
5	17.501	17.501	0.000	540.000
6	13.750	20.579	0.000	540.000
7	9.471	22.866	0.000	540.000
8	4.828	24.274	0.000	540.000
9	0.000	24.750	0.000	540.000
10	-4.828	24.274	0.000	540.000
11	-9.471	22.866	0.000	540.000
12	-13.750	20.579	0.000	540.000
13	-17.501	17.501	0.000	540.000
14	-20.579	13.750	0.000	540.000
15	-22.866	9.471	0.000	540.000
16	-24.274	4.828	0.000	540.000
17	-24.750	0.000	0.000	540.000
18	-24.750	-7.250	0.000	540.000

EQUATION NUMBERS

NODE	XX	YY	ZZ
1	1	2	3
2	1	2	3
3	1	2	3
4	1	2	3
5	1	2	3
6	1	2	3
7	1	2	3
8	1	2	3
9	1	2	3
10	1	2	3
11	1	2	3
12	1	2	3
13	1	2	3
14	1	2	3
15	1	2	3
16	1	2	3
17	1	2	3
18	1	2	3

SAPIX INPUT AND OUTPUT DATA FOR CASE 17
 (49.5 - INCH U-TUBE BEND)

CTR 1141.30

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3 / 0 B E A M E L E M E N T S

NUMBER OF BEAMS = 16
NUMBER OF GEOMETRIC PROPERTY SETS = 1
NUMBER OF FIXED END FORCE SETS = 0
NUMBER OF MATERIALS = 1

MATERIAL PROPERTIES

MATERIAL NUMBER	YOUNG'S MODULUS	POISSON'S RATIO	MASS DENSITY	WEIGHT DENSITY
1	.2940E+08	.3000	.1258E-02	0.

BEAM GEOMETRIC PROPERTIES

SECTION NUMBER	AXIAL AREA A(1)	SHEAR AREA A(2)	SHEAR AREA A(3)	TORSION J(1)	INERTIA I(2)	INERTIA I(3)
1	.6943E-01	.6943E-01	.6943E-01	.1000E+02	.2342E-02	.2342E-02

ELEMENT LOAD MULTIPLIERS

	A	B	C	D
X-DIR	0.	0.	0.	0.
Y-DIR	.100000E+01	.100000E+01	.100000E+01	.100000E+01
Z-DIR	0.	0.	0.	0.

3/0 beam ELEMENT DATA

BEAM NUMBER	NODE -I	NODE -J	NODE -K	MATERIAL NUMBER	SECTION NUMBER	ELEMENT A	END B	LOADS C	END D	CODES -I	CODES -J
1	1	2	18	1	1	0	0	0	0	0	0
2	2	3	18	1	1	0	0	0	0	0	0
3	3	4	18	1	1	0	0	0	0	0	0
4	4	5	18	1	1	0	0	0	0	0	0
5	5	6	18	1	1	0	0	0	0	0	0
6	6	7	18	1	1	0	0	0	0	0	0
7	7	8	18	1	1	0	0	0	0	0	0
8	8	9	18	1	1	0	0	0	0	0	0
9	9	10	18	1	1	0	0	0	0	0	0
10	10	11	18	1	1	0	0	0	0	0	0
11	11	12	18	1	1	0	0	0	0	0	0
12	12	13	18	1	1	0	0	0	0	0	0
13	13	14	18	1	1	0	0	0	0	0	0
14	14	15	18	1	1	0	0	0	0	0	0
15	15	16	18	1	1	0	0	0	0	0	0
16	16	17	18	1	1	0	0	0	0	0	0

EQUATION PARAMETERS

TOTAL NUMBER OF EQUATIONS ■ 96
BANDWIDTH ■ 12
NUMBER OF EQUATIONS IN A BLOCK ■ 96
NUMBER OF BLOCKS ■ 1

EQUATION PARAMETERS

TOTAL NUMBER OF EQUATIONS ■ 96
 BANDWIDTH ■ 12
 NUMBER OF EQUATIONS IN A BLOCK ■ 96
 NUMBER OF BLOCKS ■ 1

50 .5430E-01
 51 .6050E-01
 52 .6170E-01
 53 .6300E-01
 54 .6420E-01
 55 .6540E-01
 56 .6660E-01
 57 .6780E-01
 58 .6900E-01
 59 .7020E-01
 60 .7140E-01
 61 .7260E-01
 62 .7380E-01
 63 .7510E-01
 64 .7630E-01
 65 .7750E-01
 66 .7870E-01
 67 .7990E-01
 68 .8110E-01
 69 .8230E-01
 70 .8350E-01

.3090E+03
 .3090E+03
 .5880E+03
 .8090E+03
 .9510E+03
 .1000E+04
 .9510E+03
 .8090E+03
 .5880E+03
 .3090E+03
 0.
 .3090E+03
 .5880E+03
 .8090E+03
 .9510E+03
 .1000E+04
 .9510E+03
 .8090E+03
 .5880E+03
 .3090E+03

NODAL LOADS (STATIC) OR MASSES (DYNAMIC)

NODE NUMBER	LOAD CASE	X-AXIS FORCE	Y-AXIS FORCE	Z-AXIS FORCE	X-AXIS MOMENT	Y-AXIS MOMENT	Z-AXIS MOMENT
----------------	--------------	-----------------	-----------------	-----------------	------------------	------------------	------------------

STRUCTURE LOAD CASE	ELEMENT		LOAD	MULTIPLIERS	
	A	B		C	D
1	0.000	0.000	0.030	0.000	

STEP-BY-STEP SOLUTION CONTROL INFORMATION

NUMBER OF TIME VARYING FUNCTIONS	1
GROUND MOTION INDICATOR	0
EQ.0, NONE	
GT.0, READ ACCELERATION INPUT	
NUMBER OF ARRIVAL TIMES	0
EQ.0, ALL FUNCTIONS ARRIVE AT TIME ZERO	
NUMBER OF SOLUTION TIME STEPS	3000

STEP-BY-STEP SOLUTION CONTROL INFORMATION

NUMBER OF TIME VARYING FUNCTIONS - 1
 GROUND MOTION INDICATOR - 0
 EQ.0, NONE
 GT.0, READ ACCELERATION INPUT
 NUMBER OF ARRIVAL TIMES - 0
 EQ.0, ALL FUNCTIONS ARRIVE
 AT TIME ZERO
 NUMBER OF SOLUTION TIME STEPS - 3000
 OUTPUT (PRINT) INTERVAL - 1
 SOLUTION TIME INCREMENT - .2000E-02
 MASS- PROPORTIONAL DAMPING
 COEFFICIENT (ALPHA) - 0.
 STIFFNESS-PROPORTIONAL DAMPING
 COEFFICIENT (BETA) - .3570E-03

DYNAMIC LOAD INPUT

MODE NUMBER	DEGREE OF FREEDOM	FUNCTION REFERENCE	ARRIVAL TIME NUMBER	FUNCTION MULTIPLIER
1	1	1	1	.2240E-05
2	1	1	1	.2240E-05
3	1	1	1	.2240E-05
4	1	1	1	.2240E-05
5	1	1	1	.2240E-05
6	1	1	1	.2240E-05
7	1	1	1	.2240E-05
8	1	1	1	.2240E-05
9	1	1	1	.2240E-05
10	1	1	1	.2240E-05
11	1	1	1	.2240E-05
12	1	1	1	.2240E-05
13	1	1	1	.2240E-05

DYNAMIC LOAD INPUT

NODE NUMBER	DEGREE OF FREEDOM	FUNCTION REFERENCE	ARRIVAL TIME NUMBER	FUNCTION MULTIPLIER
2	3	1	1	.2240E-05
3	3	1	1	.2240E-05
4	3	1	1	.2240E-05
5	3	1	1	.2240E-05
6	3	1	1	.2240E-05
7	3	1	1	.2240E-05
9	3	1	1	.2240E-05
11	3	1	1	.2240E-05
12	3	1	1	.2240E-05
13	3	1	1	.2240E-05
14	3	1	1	.2240E-05
15	3	1	1	.2240E-05
16	3	1	1	.2240E-05

ARRIVAL TIME VALUES

INPUT ORDER	ARRIVAL TIME VALUE
1	0.

TIME FUNCTION DATA

TIME FUNCTION NUMBER = (1)

NUMBER OF POINTS = (**)
 SCALE FACTOR = (.1000E+01)
 DESCRIPTION = (TURBULENT-BUFFET LOAD ON SG TUBE)

INPUT ORDER	TIME VALUE	FUNCTION VALUE
----------------	---------------	-------------------

1	0.	0.
2	.1200E-02	.3090E+03

TIME FUNCTION DATA

TIME FUNCTION NUMBER = (1)

NUMBER OF POINTS = (**)

SCALE FACTOR = (.1000E+01)

DESCRIPTION = (TURBULENT-BUFFET LOAD ON SG TUBE)

INPUT ORDER	TIME VALUE	FUNCTION VALUE
1	0.	0.
2	.1200E-02	.3090E+03
3	.2400E-02	.5880E+03
4	.3600E-02	.8090E+03
5	.4800E-02	.9510E+03
6	.6100E-02	.1000E+04
7	.7300E-02	.9510E+03
8	.8500E-02	.8090E+03
9	.9700E-02	.5880E+03
10	.1090E-01	.3090E+03
11	.1210E-01	0.
12	.1330E-01	.3090E+03
13	.1450E-01	.5880E+03
14	.1570E-01	.8090E+03
15	.1690E-01	.9510E+03
16	.1820E-01	.1000E+04
17	.1940E-01	.9510E+03
18	.2060E-01	.8090E+03
19	.2190E-01	.5880E+03
20	.2300E-01	.3090E+03
21	.2420E-01	0.
22	.2540E-01	.3090E+03
23	.2660E-01	.5880E+03
24	.2780E-01	.8090E+03
25	.2910E-01	.9510E+03
26	.3030E-01	.1000E+04
27	.3150E-01	.9510E+03
28	.3270E-01	.8090E+03
29	.3390E-01	.5880E+03
30	.3510E-01	.3090E+03
31	.3630E-01	0.
32	.3750E-01	.3090E+03
33	.3870E-01	.5880E+03
34	.4000E-01	.8090E+03
35	.4120E-01	.9510E+03
36	.4240E-01	.1000E+04
37	.4360E-01	.9510E+03
38	.4480E-01	.8090E+03
39	.4600E-01	.5880E+03
40	.4720E-01	.3090E+03
41	.4840E-01	0.
42	.4960E-01	.3090E+03
43	.5080E-01	.5880E+03
44	.5210E-01	.8090E+03
45	.5330E-01	.9510E+03
46	.5450E-01	.1000E+04
47	.5570E-01	.9510E+03
48	.5690E-01	.8090E+03
49	.5810E-01	.5880E+03
50	.5930E-01	.3090E+03
51	.6050E-01	0.
52	.6170E-01	.3090E+03
53	.6300E-01	.5880E+03
54	.6420E-01	.8090E+03
55	.6540E-01	.9510E+03
56	.6660E-01	.1000E+04
57	.6780E-01	.9510E+03
58	.6900E-01	.8090E+03
59	.7020E-01	.5880E+03
60	.7140E-01	.3090E+03
61	.7260E-01	0.
62	.7380E-01	.3090E+03
63	.7500E-01	.5880E+03
64	.7630E-01	.8090E+03
65	.7750E-01	.9510E+03
66	.7870E-01	.1000E+04
67	.7990E-01	.9510E+03
68	.8110E-01	.8090E+03
69	.8230E-01	.5880E+03
70	.8350E-01	.3090E+03
71	.8470E-01	0.

1 .60500 -01 3 .30900 +03
2 .61700 -01 - .58800 +03
3 .63000 -01 - .80900 +03
4 .64200 -01 - .95100 +03
55 .65400 -01 - .10000 +04
56 .66600 -01 - .95100 +03
57 .67800 -01 - .80900 +03
58 .69000 -01 - .58800 +03
59 .70200 -01 .30900 +03
60 .71400 -01 0
61 .72600 -01 0
62 .73800 -01 .30900 +03
63 .75100 -01 .58800 +03
64 .76300 -01 .80900 +03
65 .77500 -01 .95100 +03
66 .78700 -01 .10000 +04
67 .79900 -01 .95100 +03
68 .81100 -01 .80900 +03
69 .82300 -01 .58800 +03
70 .83500 -01 .30900 +03
71 .84700 -01 0
72 .86000 -01 .30900 +03
73 .87200 -01 .58800 +03
74 .88400 -01 .80900 +03
75 .89600 -01 .95100 +03
76 .90800 -01 .10000 +04
77 .92000 -01 .95100 +03
78 .93200 -01 .80900 +03
79 .94400 -01 .58800 +03
80 .95600 -01 .30900 +03
81 .96900 -01 0
82 .98100 -01 .30900 +03
83 .99300 -01 .58800 +03
84 .100500 +00 .80900 +03
85 .101700 +00 .95100 +03
86 .102900 +00 .10000 +04
87 .104100 +00 .95100 +03
88 .105300 +00 .80900 +03
89 .106500 +00 .58800 +03
90 .107700 +00 .30900 +03
91 .109000 +00 0
92 .110200 +00 .30900 +03
93 .111400 +00 .58800 +03
94 .112600 +00 .80900 +03
95 .113800 +00 .95100 +03
96 .115000 +00 .10000 +04
97 .116200 +00 .95100 +03
98 .117400 +00 .80900 +03
99 .118600 +00 .58800 +03
100 .119900 +00 .30900 +03
101 .121100 +00 0
102 .122300 +00 .30900 +03
103 .123500 +00 .58800 +03
104 .124700 +00 .80900 +03
105 .125900 +00 .95100 +03
106 .127100 +00 .10000 +04
107 .128300 +00 .95100 +03
108 .129500 +00 .80900 +03
109 .130800 +00 .58800 +03
110 .132000 +00 .30900 +03
111 .133200 +00 0
112 .134400 +00 .30900 +03
113 .135600 +00 .58800 +03
114 .136800 +00 .80900 +03
115 .138000 +00 .95100 +03
116 .139200 +00 .10000 +04
117 .140400 +00 .95100 +03
118 .141600 +00 .80900 +03
119 .142800 +00 .58800 +03
120 .144000 +00 .30900 +03
121 .145300 +00 0
122 .146500 +00 .30900 +03
123 .147700 +00 .58800 +03
124 .148900 +00 .80900 +03
125 .150100 +00 .95100 +03
126 .151300 +00 .10000 +04
127 .152500 +00 .95100 +03
128 .153800 +00 .80900 +03
129 .155000 +00 .58800 +03
130 .156200 +00 .30900 +03
131 .157400 +00 0
132 .158600 +00 .30900 +03
133 .159800 +00 .58800 +03
134 .161000 +00 .80900 +03
135 .162200 +00 .95100 +03
136 .163400 +00 .10000 +04
137 .164600 +00 .95100 +03
138 .165900 +00 .80900 +03

DISPLACEMENT COMPONENT OUTPUT REQUESTS

CODE FOR OUTPUT TYPE = 2
 EQ.1, HISTORY TABLE
 EQ.2, PRINTER PLOT
 EQ.3, MAXIMA ONLY
 PRINTER PLOT SPACING = 0

NODE NUMBER	DISPLACEMENT			COMPONENT		
	*	*	*	*	*	*
4	3	0	0	0	0	0
5	3	0	0	0	0	0
13	3	0	0	0	0	0
14	3	0	0	0	0	0
0	0	0	0	0	0	0

ST S COMPONENT OUTPUT REQUESTS

CODE FOR OUTPUT TYPE = 2
 EQ.1, HISTORY TABLE
 EQ.2, PRINTER PLOT
 EQ.3, MAXIMA ONLY
 PRINTER PLOT SPACING = 0

ELEMENT TYPE (2)

ELEMENT NUMBER	DESIRE	ELEMENT	STRESS	COMPONENTS
0	0	0	0	0

EQUATION PARAMETERS

TOTAL NUMBER OF EQUATIONS	95
1/2 EQUATION BANDWIDTH	12
NUMBER OF EQUATIONS PER BLOCK	95
TOTAL NUMBER OF EQUATION BLOCKS	1
NUMBER OF COUPLING BLOCKS	0

EQUATION PARAMETERS

TOTAL NUMBER OF EQUATIONS	96
1/2-EQUATION BANDWIDTH	12
NUMBER OF EQUATIONS PER BLOCK	96
TOTAL NUMBER OF EQUATION BLOCKS	1
NUMBER OF COUPLING BLOCKS	0

NORMALIZED DISPLACEMENT HISTORY PLOT

OUTPUT SET NUMBER = 1

NODE NUMBER	DISPLACEMENT COMPONENT	MAXIMUM VALUE	TIME AT MAXIMUM	PLOT SYMBOL
4	3	7.7144E-04	2.9200E-01	1
5	3	7.0230E-04	2.9200E-01	2
13	3	7.0229E-04	2.9200E-01	3
14	3	7.7143E-04	2.9200E-01	4

ORDINATE

TIME
0.0000

-1.0

-0.5

0.0

0.5

1.0

TIME
0.0000

.0200

.0200

.0400

.0400

.0600

.0600

.0800

.0800

.1000

.1000

.1200

.1200

.1400

.1400

.1200

.1400

.1600

.1800

.2000

.2200

.2400

.2600

.2800

.1200

.1400

.1600

.1800

.2000

.2200

.2400

.2600

.2800

5.9800

5.9800

6.0000
6.00206.0000
6.0020

T I M E -1.0

-0.5

0.0

0.5

1.0

T I M E

T I M E L O G (PARTICULAR SOLUTION)

FORM DYNAMIC LOADS	74.72
PROCESS OUTPUT REQUESTS	.02
MATRIX DECOMPOSITION	.02
STEP-BY-STEP INTEGRATION	16.39
DISPLACEMENT OUTPUT	2.17
ELEMENT STRESS OUTPUT	0.00

TOTAL STEP-BY-STEP ANALYSIS 93.30

OVERLAY (25, C)

LOAD AT (31025)

PROGRAM WILL BE ENTERED AT SBSSOL (31034)

SCH LENGTH 41622

LCM LENGTH

10

BLOCK ADDRESS LENGTH

/JUNK/	114	326
/ELPAR/	452	30
/EM/	52	7714
/DYN/	10416	11
/TAPES/	10427	6
/EXTRA/	10435	20
/SOL/	10455	12
(2, 50)	31125	5
SBSSOL	31132	5
STEP	31037	1064
ADDMS	32123	112
PLDAD	32235	353
EHDS	322610	32
GRUND	32262	203
INDLY	33065	227
INTHS	33314	341
LDADV	33655	402
INDUT	34257	733
SOLSTP	35212	518
IRIFAC	35770	644
REOVN	36634	375
SDSPLY	37227	1161
SPLDT	47415	351
ELOUTS	40761	571
BACKSP	41552	50
/LCM/	0	10

SAPIV INPUT AND OUTPUT DATA FOR CASE 18
 (36-INCH U-TUBE BEND PLUS
 17.375-INCH VERTICAL EXTENSION)

CASE 16, U-TUBE SUPP. ESP/USP, DAMP=002, 36.0 D, FS=44.4, FT=41.3, FNZ=42.2, H

CONTROL INFORMATION

NUMBER OF NODAL POINTS	15
NUMBER OF ELEMENT TYPES	1
NUMBER OF LOAD CASES	1
NUMBER OF FREQUENCIES	1

CONTROL INFORMATION

NUMBER OF NODAL POINTS = 15
 NUMBER OF ELEMENT TYPES = 1
 NUMBER OF LOAD CASES = 1
 NUMBER OF FREQUENCIES = 1
 ANALYSIS CODE (NDYN) = 4
 EQ.1, STATIC
 EQ.2, MODAL EXTRACTION
 EQ.3, FORCED RESPONSE
 EQ.4, RESPONSE SPECTRUM
 EQ.5, DIRECT INTEGRATION
 SOLUTION MODE (MODEX) = 0
 EQ.0, EXECUTION
 EQ.1, DATA CHECK
 NUMBER OF SUBSPACE = 0
 ITERATION VECTORS (NAD) = 0
 EQUATIONS PER BLOCK = 0
 TAPE19 SAVE FLAG (N10SV) = 0

NODAL POINT INPUT DATA

NODE NUMBER	BOUNDARY CONDITION CODES						NODAL POINT COORDINATES				Z	T
	X	Y	Z	XX	YY	ZZ	X	Y	Z			
1	1	1	1	0	0	0	18.000	0.000	0.000	1	540.000	
2	1	1	1	0	0	0	17.146	0.000	0.000	1	540.000	
3	1	1	1	0	0	0	14.146	0.000	0.000	1	540.000	
4	1	1	1	0	0	0	9.723	0.000	0.000	1	540.000	
5	1	1	1	0	0	0	4.233	0.000	0.000	1	540.000	
6	1	1	1	0	0	0	-1.723	0.000	0.000	1	540.000	
7	1	1	1	0	0	0	-7.491	0.000	0.000	1	540.000	
8	1	1	1	0	0	0	-12.434	0.000	0.000	1	540.000	
9	1	1	1	0	0	0	-16.008	0.000	0.000	1	540.000	
10	1	1	1	0	0	0	-17.819	0.000	0.000	1	540.000	
11	1	1	1	0	0	0	-18.000	0.000	0.000	1	540.000	
12	1	1	1	0	0	0	-18.000	0.000	0.000	1	540.000	
13	1	1	1	0	0	0	-18.000	0.000	0.000	1	540.000	
14	1	1	1	0	0	0	-18.000	0.000	0.000	1	540.000	
15	1	1	1	0	0	0	-18.000	0.000	0.000	1	540.000	

GENERATED NODAL DATA

NODE NUMBER	BOUNDARY CONDITION CODES						NODAL POINT COORDINATES				Z	T
	X	Y	Z	XX	YY	ZZ	X	Y	Z			
1	1	1	1	0	0	0	18.000	0.000	0.000	1	540.000	
2	1	1	1	0	0	0	17.146	0.000	0.000	1	540.000	
3	1	1	1	0	0	0	14.146	0.000	0.000	1	540.000	
4	1	1	1	0	0	0	9.723	0.000	0.000	1	540.000	
5	1	1	1	0	0	0	4.233	0.000	0.000	1	540.000	
6	1	1	1	0	0	0	-1.723	0.000	0.000	1	540.000	
7	1	1	1	0	0	0	-7.491	0.000	0.000	1	540.000	
8	1	1	1	0	0	0	-12.434	0.000	0.000	1	540.000	
9	1	1	1	0	0	0	-16.008	0.000	0.000	1	540.000	
10	1	1	1	0	0	0	-17.819	0.000	0.000	1	540.000	
11	1	1	1	0	0	0	-18.000	0.000	0.000	1	540.000	
12	1	1	1	0	0	0	-18.000	0.000	0.000	1	540.000	
13	1	1	1	0	0	0	-18.000	0.000	0.000	1	540.000	
14	1	1	1	0	0	0	-18.000	0.000	0.000	1	540.000	
15	1	1	1	0	0	0	-18.000	0.000	0.000	1	540.000	

EQUATION NUMBERS

N	X	Y	Z	XX	YY	ZZ
1	1	1	1	1	1	1
2	1	1	1	1	1	1
3	1	1	1	1	1	1
4	1	1	1	1	1	1
5	1	1	1	1	1	1
6	1	1	1	1	1	1
7	1	1	1	1	1	1
8	1	1	1	1	1	1
9	1	1	1	1	1	1
10	1	1	1	1	1	1
11	1	1	1	1	1	1
12	1	1	1	1	1	1
13	1	1	1	1	1	1
14	1	1	1	1	1	1
15	1	1	1	1	1	1

3 / D B E A M E L E M E N T S

NUMBER OF SCAMS = 13
 NUMBER OF GEOMETRIC PROPERTY SETS = 1
 NUMBER OF FIXED END FORCE SETS = 0
 NUMBER OF MATERIALS = 1

MATERIAL PROPERTIES

MATERIAL NUMBER	YOUNG'S MODULUS	POISSON'S RATIO	MASS DENSITY	WEIGHT DENSITY
1	.2940E+08	.3000	.1258E-02	0.

BEAM GEOMETRIC PROPERTIES

SECTION NUMBER	AXIAL AREA A(1)	SHEAR AREA A(2)	SHEAR AREA A(3)	TORSION J(1)	INERTIA I(2)	INERTIA I(3)
1	.6943E-01	.6943E-01	.6943E-01	.1000E+02	.2201E-02	.2201E-02

ELEMENT LOAD MULTIPLIERS

	A	B	C	D
X-DIR	0.	0.	0.	0.
Y-DIR	.100000E+01	.100000E+01	.100000E+01	.100000E+01
Z-DIR	0.	0.	0.	0.

3/D BEAM ELEMENT DATA

BEAM NUMBER	NODE J	NODE K	NODE L	MATERIAL NUMBER	SECTION NUMBER	ELEMENT	END LOADS	END CODES			
						A	B	C	D	E	F
1	1	2	3	1	1	0	0	0	0	0	0
2	2	3	4	1	1	0	0	0	0	0	0
3	3	4	5	1	1	0	0	0	0	0	0
4	4	5	6	1	1	0	0	0	0	0	0
5	5	6	7	1	1	0	0	0	0	0	0
6	6	7	8	1	1	0	0	0	0	0	0
7	7	8	9	1	1	0	0	0	0	0	0
8	8	9	10	1	1	0	0	0	0	0	0
9	9	10	11	1	1	0	0	0	0	0	0
10	10	11	12	1	1	0	0	0	0	0	0
11	11	12	13	1	1	0	0	0	0	0	0
12	12	13	14	1	1	0	0	0	0	0	0
13	13	14	15	1	1	0	0	0	0	0	0

3/D BEAM ELEMENT DATA

BEAM NUMBER	NODE -I	NODE -J	NODE -K	MATERIAL NUMBER	SECTION NUMBER	ELEMENT A	END B	LOADS C	LOADS D	END -I	END -J
1	1	2	15	1	1	0	0	0	0	0	0
2	3	4	15	1	1	0	0	0	0	0	0
3	5	6	15	1	1	0	0	0	0	0	0
4	7	8	15	1	1	0	0	0	0	0	0
5	9	10	15	1	1	0	0	0	0	0	0
6	11	12	15	1	1	0	0	0	0	0	0
7	13	14	15	1	1	0	0	0	0	0	0
8	15	16	15	1	1	0	0	0	0	0	0
9	17	18	15	1	1	0	0	0	0	0	0
10	19	20	15	1	1	0	0	0	0	0	0
11	21	22	15	1	1	0	0	0	0	0	0
12	23	24	15	1	1	0	0	0	0	0	0
13	25	26	15	1	1	0	0	0	0	0	0

EQUATION PARAMETERS
TOTAL NUMBER OF EQUATIONS ■ 76
BANDWIDTH ■ 12
NUMBER OF EQUATIONS IN A BLOCK ■ 76
NUMBER OF BLOCKS ■ 1

EQUATION PARAMETERS

TOTAL NUMBER OF EQUATIONS ■ 76
 BANDWIDTH ■ 12
 NUMBER OF EQUATIONS IN A BLOCK ■ 76
 NUMBER OF BLOCKS ■ 1

NODAL LOADS (STATIC) OR MASSES (DYNAMIC)

NODE NUMBER	LOAD CASE	X-AXIS FORCE	Y-AXIS FORCE	Z-AXIS FORCE	X-AXIS MOMENT	Y-AXIS MOMENT	Z-AXIS MOMENT
----------------	--------------	-----------------	-----------------	-----------------	------------------	------------------	------------------

STRUCTURE
LOAD CASE

ELEMENT LOAD MULTIPLIERS

1	0.000	0.000	0.000	0.000
---	-------	-------	-------	-------

NODAL LOADS (STATIC) OR MASSES (DYNAMIC)

NODE NUMBER	LOAD CASE	X-AXIS FORCE	Y-AXIS FORCE	Z-AXIS FORCE	X-AXIS MOMENT	Y-AXIS MOMENT	Z-AXIS MOMENT
----------------	--------------	-----------------	-----------------	-----------------	------------------	------------------	------------------

STRUCTURE LOAD CASE	ELEMENT		LOAD B	MULTIPLIERS	
	A	C		D	E
1	0.000	0.000	0.000	0.000	0.000

STEP-BY-STEP SOLUTION CONTROL INFORMATION

NUMBER OF TIME VARYING FUNCTIONS = 1

GROUND MOTION INDICATOR = 0
 EQ.0, NONE
 GT.0, READ ACCELERATION INPUT

NUMBER OF ARRIVAL TIMES = 0
 EQ.0, ALL FUNCTIONS ARRIVE
 AT TIME ZERO

NUMBER OF SOLUTION TIME STEPS = 2000

TIME STEP INTERVAL = 1

STEP-BY-STEP SOLUTION CONTROL INFORMATION

NUMBER OF TIME VARYING FUNCTIONS = 1

GROUND MOTION INDICATOR = 0

EQ.0, NONE

GT.0, READ ACCELERATION INPUT

NUMBER OF ARRIVAL TIMES = 0

EQ.0, ALL FUNCTIONS ARRIVE
AT TIME ZERO

NUMBER OF SOLUTION TIME STEPS = 5000

OUTPUT (PRINT) INTERVAL = 1

SOLUTION TIME INCREMENT = .2000E-02

MASS-PPROPORTIONAL DAMPING
COEFFICIENT (ALPHA) = 6.

STIFFNESS-PPROPORTIONAL DAMPING
COEFFICIENT (BETA) = .3320E-03

DYNAMIC LOAD INPUT

NODE NUMBER	DEGREE OF FREEDOM	FUNCTION REFERENCE	ARRIVAL TIME NUMBER	FUNCTION MULTIPLIER
2	3	1	1	.5760E-03
3	3	1	1	.5760E-03
4	3	1	1	.5760E-03
7	3	1	1	.5760E-03
8	3	1	1	.5760E-03
9	3	1	1	.5760E-03
10	3	1	1	.5760E-03

DYN I C L O A D I N P U T				
NOD NUMBER	DEGREE OF FREEDOM	FUNCTION REFERENCE	ARRIVAL TIME NUMBER	FUNCTION MULTIPLIER
2	3	1	1	.5760E-05
3	3	1	1	.5760E-05
4	3	1	1	.5760E-05
7	3	1	1	.5760E-05
8	3	1	1	.5760E-05
9	3	1	1	.5760E-05
10	3	1	1	.5760E-05

ARRIVAL TIME VALUES

INPUT ORDER	ARRIVAL TIME VALUE
1	0.

TIME FUNCTION DATA

TIME FUNCTION NUMBER = (1)

NUMBER OF POINTS = (***)

SCALE FACTOR = (.1000E+01)

DESCRIPTION = (TURBULENT-BUFFETING FORCE ON U-TUBES)

INPUT ORDER	TIME VALUE	FUNCTION VALUE
1	0.	0.
2	.1270E-02	.3790E+03
3	.2400E-02	.5880E+03

TIME FUNCTION DATA

TIME FUNCTION NUMBER = (1)

NUMBER OF POINTS = (***)

SCALE FACTOR = (10000+01)

DESCRIPTION = (TURBULENT-BUFFETING FORCE ON U-TUBES)

INPUT ORDER TIME VALUE FUNCTION VALUE

1	C.	0.
2	.12700	.34900
3	.24000	.38800
4	.36000	.80900
5	.48000	.92100
6	.61000	.15000
7	.73000	.45100
8	.85000	.85000
9	.97000	.50800
10	1.09000	.30900
11	1.21000	.30900
12	1.33000	.30900
13	1.45000	.30900
14	1.57000	.30900
15	1.69000	.30900
16	1.82000	.30900
17	1.94000	.30900
18	2.06000	.30900
19	2.18000	.30900
20	2.30000	.30900
21	2.42000	.30900
22	2.54000	.30900
23	2.66000	.30900
24	2.78000	.30900
25	2.90000	.30900
26	3.02000	.30900
27	3.14000	.30900
28	3.26000	.30900
29	3.38000	.30900
30	3.50000	.30900
31	3.62000	.30900
32	3.74000	.30900
33	3.86000	.30900
34	3.98000	.30900
35	4.10000	.30900
36	4.22000	.30900
37	4.34000	.30900
38	4.46000	.30900
39	4.58000	.30900
40	4.70000	.30900
41	4.82000	.30900
42	4.94000	.30900
43	5.06000	.30900
44	5.18000	.30900
45	5.30000	.30900
46	5.42000	.30900
47	5.54000	.30900
48	5.66000	.30900
49	5.78000	.30900
50	5.90000	.30900
51	6.02000	.30900
52	6.14000	.30900
53	6.26000	.30900
54	6.38000	.30900
55	6.50000	.30900
56	6.62000	.30900
57	6.74000	.30900
58	6.86000	.30900
59	6.98000	.30900
60	7.10000	.30900
61	7.22000	.30900
62	7.34000	.30900
63	7.46000	.30900
64	7.58000	.30900
65	7.70000	.30900
66	7.82000	.30900
67	7.94000	.30900
68	8.06000	.30900
69	8.18000	.30900
70	8.30000	.30900
71	8.42000	.30900
72	8.54000	.30900
73	8.66000	.30900
74	8.78000	.30900
75	8.90000	.30900
76	9.02000	.30900
77	9.14000	.30900
78	9.26000	.30900
79	9.38000	.30900
80	9.50000	.30900
81	9.62000	.30900
82	9.74000	.30900
83	9.86000	.30900
84	9.98000	.30900
85	10.10000	.30900
86	10.22000	.30900
87	10.34000	.30900
88	10.46000	.30900
89	10.58000	.30900
90	10.70000	.30900
91	10.82000	.30900
92	10.94000	.30900
93	11.06000	.30900
94	11.18000	.30900
95	11.30000	.30900
96	11.42000	.30900
97	11.54000	.30900
98	11.66000	.30900
99	11.78000	.30900
100	11.90000	.30900

[illegible]

```
CODE FOR OUTPUT TYPE = 2
EQ.1, HISTORY TABLE
EQ.2, PRINTER PLOT
EQ.3, MAXIMA ONLY
PRINTER PLOT SPACING = 0
```

NODE NUMBER	DISPLACEMENT COMPONENT
1	1
2	1
3	1
4	1
5	1
6	1
7	1
8	1
9	1
10	1
11	1
12	1
13	1
14	1
15	1
16	1
17	1
18	1
19	1
20	1
21	1
22	1
23	1
24	1
25	1
26	1
27	1
28	1
29	1
30	1
31	1
32	1
33	1
34	1
35	1
36	1
37	1
38	1
39	1
40	1
41	1
42	1
43	1
44	1
45	1
46	1
47	1
48	1
49	1
50	1
51	1
52	1
53	1
54	1
55	1
56	1
57	1
58	1
59	1
60	1
61	1
62	1
63	1
64	1
65	1
66	1
67	1
68	1
69	1
70	1
71	1
72	1
73	1
74	1
75	1
76	1
77	1
78	1
79	1
80	1
81	1
82	1
83	1
84	1
85	1
86	1
87	1
88	1
89	1
90	1
91	1
92	1
93	1
94	1
95	1
96	1
97	1
98	1
99	1
100	1

00000000

STRESS COMPONENT OUTPUT REQUESTS

CODE FOR OUTPUT TYPE = 2
 EQ.1, HISTORY TABLE
 EQ.2, PRINTER PLOT
 EQ.3, MAXIMA ONLY
 PRINTER PLOT SPACING = 0

NODE NUMBER	DISPLACEMENT			COMPONENT		
	X	Y	Z	1	2	3
8	3	0	0	0	0	0
9	3	0	0	0	0	0
10	3	0	0	0	0	0
11	3	0	0	0	0	0
12	3	0	0	0	0	0

STRESS COMPONENT OUTPUT REQUESTS

CODE FOR OUTPUT TYPE = 3
 EQ.1, HISTORY TABLE
 EQ.2, PRINTER PLOT
 EQ.3, MAXIMA ONLY
 PRINTER PLOT SPACING = 0

ELEMENT TYPE (2)

ELEMENT DESIRED ELEMENT STRESS COMPONENTS

STRESS COMPONENT OUTPUT REQUESTS

CODE FOR OUTPUT TYPE = 3
 EQ.1, HISTORY TABLE
 EQ.2, PRINTER PLOT
 EQ.3, MAXIMA ONLY
 PRINTER PLOT SPACING = 0

ELEMENT TYPE (2)

ELEMENT NUMBER	DESIRED ELEMENT STRESS COMPONENTS											
0	0	0	0	0	0	0	0	0	0	0	0	0

EQUATION PARAMETERS

TOTAL NUMBER OF EQUATIONS	=	76
1/2 EQUATION BANDWIDTH	=	12
NUMBER OF EQUATIONS PER BLOCK	=	76
TOTAL NUMBER OF EQUATION BLOCKS	=	1
NUMBER OF COUPLING BLOCKS	=	0

EQUATION PARAMETERS

TOTAL NUMBER OF EQUATIONS ■ 76
 1/2 EQUATION BANDWIDTH ■ 12
 NUMBER OF EQUATIONS PER BLOCK ■ 76
 TOTAL NUMBER OF EQUATION BLOCKS ■ 1
 NUMBER OF COUPLING BLOCKS ■ 0

NORMALIZED DISPLACEMENT HISTORY PLOT

OUTPUT SET NUMBER ■ 1

NODE NUMBER	DISPLACEMENT COMPONENT	MAXIMUM VALUE	TIME AT MAXIMUM	PLOT SYMBOL
8	3	2.5821E-04	2.8000E-02	1
9	3	4.1164E-04	2.8000E-02	2
10	3	4.8530E-04	2.8000E-02	3
11	3	4.2420E-04	2.8000E-02	4

OUTPUT SET N R = 1

NODE NUMBER	DISPLACEMENT COMPONENT	MAXIMUM VALUE	TIME AT MAXIMUM	PLOT SYMBOL
8	3	2.5821E-04	2.8000E-02	1
9	3	4.1164E-04	2.8000E-02	2
10	3	4.8830E-04	2.8000E-02	3
11	3	4.2920E-04	2.8000E-02	4

ORIGINATE

TIME -1.0
0.0000

0.5
1.0

TIME
0.0000

.0200

.0200

.0400

.0400

.0600

.0600

.0800

.0800

.1000

.1000

.1200

.1200

.1400

.1400

.1400

.1400

.1600

.1600

.1800

.1800

.2000

.2000

.2200

.2200

.2400

.2400

.2600

.2600

.2800

.2800

.2600

.2800

.3000

.3200

.3400

.3600

.3800

.4000

.4200

.2600

.2800

.3000

.3200

.3400

.3600

.3800

.4000

.4200

APPENDIX H

Flow Parameters for LOFT Steam
Generator Straight-Tube Sections

A linear quality gradient from inlet to outlet was assumed, in order to estimate the shell side LOFT Steam Generator flow parameters in the straight-tube sections. The results of the calculations are given in Table H-I.

LOFT STEAM GENERATOR FLOW PARAMETERS

	(34) Mass Flowrate (lbm/sec)	$\dot{m}_c = w_c =$ 122.0 ($X_T = 0.5$)	$\dot{m}_c = w_c =$ 183.0 ($X_T = 0.333$)	$Z = \text{AXIAL LOCATION}$ (FROM TUBE SHEET UPPER FACE)
(Top Bay) RADIAL IN BUNDLE AT TOP (below ESP)	Quality, X (linear gradient) $\left(\frac{\dot{m}}{A_{rf}}\right) \left(\frac{\text{lbm}}{\text{sec ft}^2}\right)$ v ($\frac{\text{ft}^3}{\text{lbm}}$) u_r ($\frac{\text{ft}}{\text{sec}}$) $q_r = \frac{u_r^2}{288 g_c v} \text{ (lb}_f/\text{in}^2)$	$X = X_T = 0.5$ 32.79 0.277 9.1 fps .0321 psi	$X = X_T = 0.333$ 49.18 0.1915 9.42 fps .04999 ~ .05 psi	$Z = 69.5$ "
AXIAL BELOW END SUPPORT PLATE (ESP)	$\left(\frac{\dot{m}}{A_{af}}\right) \left(\frac{\text{lbm}}{\text{ft}^2 \text{ sec}}\right)$ v ($\frac{\text{ft}^3}{\text{lbm}}$) u_a ($\frac{\text{ft}}{\text{sec}}$) $q_a = \frac{u_a^2}{288 g_c v} \text{ (psi)}$	$X = X_T = 0.5$ 27.06 0.277 7.50 .02189 psi	$X = X_T = 0.333$ 40.59 0.1915 7.77 .0340 psi	$Z = 69.5$ "
Middle Bay RADIAL IN BUNDLE, HALFWAY UP, &	Quality, X (linear gradient) $\left(\frac{\dot{m}}{A_{rf}}\right) \left(\frac{\text{lbm}}{\text{sec ft}^2}\right)$ v ($\frac{\text{ft}^3}{\text{lbm}}$) u_r (fps) $q_r = \frac{u_r^2}{288 g_c v} \text{ (psi)}$	$X = \frac{(Z-12)}{57.5} X_T = 0.1978$ 32.79 0.1223 4.01 .01419 psi	$X = \frac{(Z-12)}{57.5} X_T = 0.132$ 49.18 .08863 4.36 .02315 psi	$Z = 34.75$ "

FLOW PARAMETERS

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H-3

Mass
Flowrate
(lbm/sec)

$$\dot{m}_c = w_c = 122$$

$$(X_T = 0.5)$$

$$\dot{m}_c = w_c =$$

$$183.0 (X_T = 0.333)$$

Z = Axial
Location
from
Tubesheet
Upper Face

Middle
Bay, G
Axial
in
Bundle,
Halfway
Up

$$A_{af} = 4.508$$

$$\left(\frac{\dot{m}}{A_{af}} \right)$$

$$v$$

$$u_a$$

$$g_a = \frac{u_a^2}{288 g_c v}$$

$$0.1978$$

$$27.06$$

$$0.1223$$

$$13.31$$

$$.00967 \text{ psi}$$

$$0.132$$

$$40.59$$

$$0.08863$$

$$3.60$$

$$.0158 \text{ psi}$$

$$Z = 34.75''$$

Mass
Flowrate

$$\dot{m}_c = 122$$

$$(X_T = 0.5)$$

$$\dot{m}_c = 183$$

$$(X_T = 0.333)$$

Z = Air
Location
from
Tubesheet
Upper Face

Quality, X (linear gradient)

$$\left(\frac{Z-12}{57.5}\right) X_T = X = 0,$$

$$Arf = 3.721 \text{ ft}^2$$

$$X = 0.$$

$$Z = 8.6875''$$

Radial
in
Bundle,
Lower
Bay,
E

$$\left(\frac{\dot{m}}{Arf}\right)$$

$$32.79$$

$$49.18$$

$$\sqrt{}$$

$$.02105$$

$$.02105$$

$$u_r$$

$$0.69$$

$$1.04$$

$$g_r = \frac{u_r^2}{288 g_c \sqrt{}}$$

$$.002441 \text{ psi}$$

$$.00555 \text{ psi}$$

^{Cross} Max. Flow Velocity on Outer Tubes of Bundle

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ASSUMPTIONS: $50\% > x_{top} > 33\%$

- 1) $122 < w_c < 183$ lbm/sec.
- 2) Uniform axial velocity profile radially across bundle (Uniform mass flux distribution)
 -- (leakage through 3/16" holes in baffle plates helps make the flows uniform.)
- 3) All mass flow assumed to go around lip of baffle (leakage through 3/16" holes neglected for velocity calculations)
- 4) Cross flow velocity related to axial velocity by ratio of cross-section areas in the two directions.

$$\text{Axial velocity} = \frac{\dot{m}}{A_{\text{axial flow}}} = \frac{\dot{m}}{A_{af}}$$

$$\text{Axial flow area, } A_{af} \approx \frac{1}{2} \left[\pi/4 (ID_{\text{shroud}})^2 - 3690 \pi/4 (0.5)^2 \right]$$

$$A_{af} \approx \frac{1}{2} \left[\pi/4 (50.75)^2 - 3690 \pi/4 (0.5)^2 \right]$$

$$A_{af} \approx 649.2 \text{ in}^2 = 4.508 \text{ ft}^2$$

Centerline
 (a) Radial Flow
 Area, $A_{rf} =$

Maximum velocity occurs at top of bundle where x and v_1 are greatest.

$$x = x(\text{top of bundle}) = \frac{33}{100} = 0.33 \text{ for } 183 \frac{\text{lbm}}{\text{sec}}$$

$$= 0.50 \text{ for } 122 \frac{\text{lbm}}{\text{sec}}$$

Bundle
Centerline Radial Flow Area = A_{rf}

$$A_{rf} = (16\frac{7}{8})(50.75) - (38)(16\frac{7}{8})(0.5)$$

$$A_{rf} = 535.8 \text{ in}^2 = 3.721 \text{ ft}^2$$

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Velocities for $\dot{m} = 183 \text{ lbm/sec}$ at Top of Bundle

$$\left(\frac{\dot{m}}{A_{af}}\right) = \frac{183 \text{ lbm/sec}}{4.508 \text{ ft}^2} = 40.59 \frac{\text{lbm}}{\text{sec ft}^2}$$

$$\left(\frac{\dot{m}}{A_{rf}}\right) = \frac{183 \text{ lbm/sec}}{3.721 \text{ ft}^2} = 49.18 \frac{\text{lbm}}{\text{sec ft}^2}$$

$$P = 850 \text{ psia}$$

$$V = V_f(850) + X V_{fg}(850)$$

$$V_{183} = 0.02105 + (0.333)(0.51197) = 0.1915 \text{ ft}^3/\text{lbm}$$
~~$$V_{122} = 0.02105 + (0.333)(0.51197) = 0.1915 \text{ ft}^3/\text{lbm}$$~~

$$U_a = U_{axial} = \frac{\dot{m} V}{A_{af}} = \left(\frac{\dot{m}}{A_{af}}\right) V = (40.59)(0.1915) = 7.77 \text{ ft/sec}$$

$$U_r = U_{radial} = \left(\frac{\dot{m}}{A_{rf}}\right) V = (49.18)(0.1915) = 9.42 \text{ ft/sec}$$

Velocities for $\dot{m} = 122 \text{ lbm/sec}$ at Top of Bundle

$$\left(\frac{\dot{m}}{A_{af}}\right) = \frac{122}{4.508} = 27.06 \text{ lbm/ft}^2\text{/sec}$$

$$\left(\frac{\dot{m}}{A_{rf}}\right) = \frac{122}{3.721} = 32.79 \text{ lbm/ft}^2\text{/sec}$$

$$P = 850 \text{ psia}$$

$$v_{122} = v_f + x v_{fg} = 0.277$$

$$u_a = \left(\frac{\dot{m}}{A_{af}}\right) v = (27.06)(0.277) = 7.50 \text{ fps}$$

$$u_r = \left(\frac{\dot{m}}{A_{rf}}\right) v = (32.79)(0.277) = 9.1 \text{ fps}$$

EG&G Idaho

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REMARKS: See attachment 1 for resolution of recommendations.

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Attachment 1 to
Transmittal R-2960

This analysis was performed under WBS 521515, nodes NF 953-957 to determine if tube flow induced vibration was anticipated to be a problem for the LOFT steam generator. The analysis concluded that flow induced tube vibration should not cause tube failure during its intended operational life. Gross flow instabilities within the steam generator could cause tube damage. If such an instability occurred it would be detected during operation and a subsequent investigation would be initiated to assess the effect on the plant at the instability prior to resumption of operation.

The tubes are periodically inspected to detect tube damage utilizing the eddy current technique as part of the LOFT requalification program. A baseline was obtained in 1976. The next scheduled inspection is tentatively to be performed after the L2 series. Subsequent inspection intervals will be determined from the post L2 series results.

If a tube failure does occur between eddy current testing, the primary to secondary coolant leakage will be detected by routine monitoring of the secondary coolant gross activity. Once such leakage is detected the problem will be assessed and corrected if required prior to resumption of operation.