4. TSP Deflection Analysis

4.1 Static Analysis

4.1.1 Analysis Overview

As a precursor to performing a full bundle dynamic analysis to determine relative tube / TSP displacements for the bounding SLB loads, a preliminary analysis was performed using statically applied pressure loads. The preliminary analysis was performed to identify the number and location of expanded tubes within the lower region of the tube bundle hot leg for limiting TSP displacements under SLB loads.

The analysis was performed using the finite element model shown in Figure 6.15 of WCAP-15163, Revision 1 (hereafter referred to as the WCAP). However, for the preliminary analysis only the tube support plates of interest, Plates C, F, and J (see Figure 6.1 of the WCAP) are loaded. All remaining structures are active in the model, thus maintaining the interaction effects between the plates, wrapper, shell, tubesheet, stayrods and spacers.

Because this is an elastic static calculation, a reference load of 1 psid is applied to the tube support plates and the results scaled to higher loads as applicable. For the initial runs to identify the number and location of the expanded tubes, only Plate C was active in the model, with Plates F and J active for the final runs. Load cases were evaluated for pressure drops in both the upward and downward directions. For the case of upward loads, the wedge supports at the plate / wrapper interface were active. However, for the downward loads the wedge supports were not active as the wedges do not provide any restraint to plate motion in the down direction. Relative to the interface between the plates and the stayrods and spacers, the plates were coupled to the stayrods through the spacers for upward loads. For loads in the downward direction, the plates were coupled to the spacers which transmitted the load to the tubesheet.

In determining the number and location of the expanded tubes, the objective was to show that for pressure loads significantly above the bounding pressure load of 3.56 psid that the structural response would remain elastic, and that the peak plate displacements would not exceed 0.3”.

4.1.2 Expansion Zone Stiffness

When incorporating the restraining effect of the expanded tubes in the structural model, it is necessary to accurately represent the stiffness of the TSP expansion joint. The stiffness of the expansions is based on test data for prototypic expansions. Initially, the structural model conservatively used a stiffness of [ ] a,b,c lb/in for the TSP expansion joint; however, for later analysis cases, a more realistic stiffness

value of [ ] a,b,c lb/in was used. A schematic of the stiffness representation for the tube support plate intersection is shown in Figure 4.1.

4.1.3 Cases Analyzed

A number of different load cases were considered, varying the number and location of the expanded tubes, as well as the expansion stiffness of the tube expansion zone. The results for the initial cases without expansions and the cases with the final tube expansion locations are provided on the following pages. A summary of the input parameters for the final cases is provided in Table 4.1. It should be noted that the number of tube expansions in Table 4.1 corresponds to one-half of the hot leg, such that the total number of expansions for the bundle is twice the number shown.

Load cases 102 and 103 served to provide a reference condition, providing displacement results for the plates as well as the resulting stresses for the plates and stayrods for the case without tube expansion. Load case 112 corresponds to the final set of tube expansions with pressure load applied only to only Plate C. The final load case, Case 111, shows the effects of applying the bounding load to Plates C, F, and J simultaneously.

4.1.4 Expanded Tube Locations

As mentioned above, a number of cases were run varying the number and location of the expanded tubes. A summary of the final set of expanded tubes is provided in Table 4.2. The table provides a summary of the tube locations as well as the corresponding node in the finite element model. Note that the node locations do not match the tube positions exactly, but are generally within half an inch of the tube position. This should not have a significant effect of the plate displacements. Figure 4.2 shows the location on the expanded tubes superimposed on the finite element model grid for the tube support plate.

4.1.5 Maximum Plate Displacements

A summary of the resulting plate displacements for the cases considered is provided in Table 4.3. Results for Cases 102 and 103 show that the limiting condition is for load in the upward direction, thus subsequent cases only considered the upward loading condition. Based on the results for the Plate C, it was judged that eight tube expansions (16 for the full bundle) provided substantial stiffening of the tube support plate and provided significant margin relative to the bounding pressure load of 3.56 psid in order to limit the maximum plate displacement to less than 0.3”. As expected, due to the plate interaction effects, applying load to Plates F and J also affects the response for Plate C since the loads are transmitted through the expanded tubes. As the upper plates (above plate J) are loaded, there will also be an effect on the lower plates, however, the effect will not be as large, as the upper plates are coupled to the lower plates only at the stayrod locations and not at the

expanded tube locations. The stayrod design cannot transmit tensile loads from a higher TSP to a lower TSP, but extension of the stayrods can relieve the constraint against upward deflection on the lower TSPs.

4.1.6 Component Stresses

The validity of the elastic static analysis is contingent on the component structures remaining elastic under the applied load. The limiting components under the applied loads are the tube support plates. Table 4.4 provides a summary of the maximum tube support plate stresses. These stresses represent the average stress across a plate ligament between holes. These stresses are calculated by applying a concentration factor to the equivalent plate stresses obtained from the finite element model.

The stress concentration factors are obtained from separate finite element model analyses of representative tube support plate sections. Two models are evaluated, one in the pitch direction of the square hole pattern and a second in the pitch direction. Moments are applied to the edges of the models, varying the biaxiality ratio of the applied moments from –1.0 to 1.0. The average stress across the ligament calculated using the finite element model are then compared to the equivalent solid plate stress and a stress concentration factor developed. The corresponding concentration factors are then applied to the stresses from the finite element model as a function of biaxiality of the stresses.

The maximum plate stresses summarized in Table 4.4 occur at very localized locations in the plate, with the stresses in the majority of the plate well below yield. These stresses also represent the bending stress at the surface of the plate, and not the development of a plastic hinge in any given ligament. The yield stress in the analysis is based on the minimum acceptable yield stress as defined in the material specification for the plates scaled to high temperature conditions using the ASME Code temperature dependent strength properties.

Stresses in the stayrods and spacers are summarized in Table 4.5. Although the stresses in these components will increase when pressure loads are applied to the remaining plates, significant margin exists relative to yield for the load conditions analyzed.

4.1.7 Expanded Tube Extensions / Stresses

The expansion zone stiffness used in the above calculations are based on pull tests of prototypic expansions. The test results show the expansion zone stiffness to be linear for differential displacements in the expansion zone of 100 mils or less. After 100 mils of displacement, the stiffness of the joints declines, although the restraint force remains constant for a significantly larger deflection. (The stiffness response is comparable to elastic / plastic material response.) A summary of the expansion joint extensions as a result of the applied loads is provided in Table 4.6.

Calculations are also performed to determine the pressure load that would result in an expansion zone extension of 100 mils in the based on the limiting location.

The stresses in the expanded tubes are also of interest. In order for the elastic analysis to remain valid, these stresses must also be less than yield. A summary of the stresses in the expanded tube elements is provided in Table 4.7

4.1.8 Plate Displacement Distribution

Table 4-3 provides a summary of the maximum plate displacements. Also of interest is the distribution of plate displacements by tube location. Tables 4.8 through 4.13 provide a summary of the plate displacements by tube location. In order to determine the plate displacement at any given tube location, the following process was followed.

1. Overlay the finite element grid on top of the tube array and determine what element overlays each tube location.
2. Extract the displacement for each of the nodes comprising the element that surrounds any given tube location.
3. Interpolate the nodal displacements based on the location of the tube inside the element.
4. Group the plate displacements at the tube locations into one on 10 groupings based on the maximum displacement anywhere on the plate.

4.2 Summary

The unit (1 psid) loading analysis provides the basis for determining the factors of safety that apply for the bounding loads developed in Section 3.

The principal criterion for evaluating the factors of safety is the maximum TSP displacement. Although the maximum displacement is localized on the TSP, a displacement limit of 0.3" was established because this value, when applied at every HL intersection at every TSP (Plates C through R) provides a probability of burst less than 10^{-5}, compared to the limit of 10^{-2} specified in GL 95-05.

Other potentially limiting criteria derive from the application of the elastic model. To preserve the validity of the deflection predictions, the elements of the model must remain elastic. Thus, the following criteria were also examined in the analysis:

- TSP ligament stress must be less than the TSP yield strength at operating temperature
- Stayrod and spacer stress must be less than the stayrod and spacer yield strengths at operating temperature

- The axial deflection in the TSP expansions must be less than 0.10”
- The stresses in the expanded tubes must remain within the elastic limit

Table 4.14 summarizes the factors of safety above he peak bounding load for each of these criteria for the key cases considered in the analysis. Cases 102 and 103 provide a baseline for “up” and “down” loading of the TSPs without expanded tubes. These two cases also show that the bounding deflection is due to “up” loads; therefore, “down” loads were not analyzed for the subsequent model variations. It is noted that the TSP without tube expansions meets all deflection and stress criteria noted above.

Case 112 provides the best representation of the margins to the peak bounding load for the TSP with 16 tube expansions. The minimum factor of safety is 3.74, based on the expanded tube yield criterion. For the pressure drop associated with this factor of safety (i.e., 3.74 x 3.56 = 13.33 psid), the predicted maximum local TSP deflection is 0.18”.

Case 111 provides results for the simultaneous loading of 3 TSPs with the bounding load. This case is considered unnecessarily conservative, since the actual peak loading on the plates C, F and J is much less than the peak bounding load (3.56 psid) applicable at Plate R, and the bounding “up” load for plates C and F are much less than the predicted bounding load at Plate J (see Table 3.2). The minimum factor of safety for Case 111 (TSPs C , F and J loaded simultaneously with the peak bounding load) is 1.29, defined by the stress in the expanded tubes.

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Table 4.1
Summary of Load Cases Considered

Case	Applied Load (psi)	Plates Active	Number of Tube Expansions(1)	Expansion Stiffness (lb/in)
102	1.0	C	---	
103	-1.0	C	---	
112	1.0	C	8	a, c [ ]
111	1.0 (All Plates)	C, F, J	8	

(1) - Corresponds to one-half of hot leg. Total number of expansions is twice the number shown.

Table 4.2
Summary of Expanded Tube Locations

a,c

[ ]

Note: If selected tubes are plugged, nearest adjacent tube will be selected

Table 4.3
Summary of Maximum Plate Displacements

Case	Applied Load (psi)	Plates Active	Numer of Tube Expansions*	Expansion Stiffness (lb/in)	Maximum Vertical Displacement (inch)		Pressure Load to Cause 0.30" Displacement (psi)
102	1.0	C	---		Plate C	0.0808	3.7
103	-1.0	C	---	a, c	Plate C	-0.0565	-5.3
112	1.0	C	8	[ ]	Plate C	0.0135	22.2
111	1.0 (All Plates)	C, F, J	8		Plate C	0.0240	12.5
					Plate F	0.0254	11.8
					Plate J	0.0282	10.6

* - Corresponds to one-half of hot leg. Total number of expansions is twice the number shown.

Table 4.4
Summary of Maximum Plate Stresses

Case	Applied Load (psi)	Plates Active	Numer of Tube Expansions*	Expansion Stiffness (lb/in)	Stress (psi)		Pressure Load to Cause Support Plate to Yield (psi)
102	1.0	C	---		Plate C	9554.0	3.5
103	-1.0	C	---	a, c	Plate C	9866.0	3.4
112	1.0	C	8	[ ]	Plate C	2379.0	14.2
111	1.0 (All Plates)	C, F, J	8		Plate C	2800.0	12.1
					Plate F	2500.0	13.6
					Plate J	3150.0	10.8

* - Corresponds to one-half of hot leg. Total number of expansions is twice the number shown.

Support Plate Yield Stress = 33,900 psi

Table 4.5
Summary of Stayrod / Spacer Stresses

Case	Applied Load (psi)	Plates Active	Numer of Tube Expansions*	Expansion Stiffness (lb/in)	Element	Stress (psi)	Pressure Load to Cause Stayrod / Spacer to Yield (psi)
102	1.0	C	---		8650	682.0	49.9
					8661	679.0	50.1
					8672	1064.0	32.0
					8683	788.0	43.1
103	-1.0	C	---		8651,2	-603.0	-44.6
					8662,3	-700.0	-38.4
				a, c	8673,4	-1006.0	-26.7
					8684,5	-677.0	-39.7
112	1.0	C	8	[ ]	8650	257.0	132.3
					8661	299.0	113.7
					8672	361.0	94.2
					8683	131.0	259.5
111	1.0 (All Plates)	C, F, J	8		8650	651.0	52.2
					8661	732.0	46.4
					8672	909.0	37.4
					8683	411.0	82.7

Stayrod Yield Stress = 34,000 psi   Spacer Yield Stress = 26,900 psi

*Corresponds to one-half of hot leg. Total number of expansions is twice the number shown.

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Table 4.6
Summary of Tube Expansion Zone Extensions

Case	Tube Support Plate C		Tube Support Plate F		Tube Support Plate J		Pressure Load to Cause 0.10 inch Expansion Extension (psi)
	Element	Element Extension (inch)	Element	Element Extension (inch)	Element	Element Extension (inch)	
102	Not Aplicable						
103	Not Aplicable						
112	8748	0.0056	8749	N.A.	8750	N.A.	17.86
	8755	0.0060	8756	N.A.	8757	N.A.	16.67
	8762	0.0041	8763	N.A.	8764	N.A.	24.39
	8769	0.0063	8770	N.A.	8771	N.A.	15.87
	8776	0.0055	8777	N.A.	8778	N.A.	18.18
	8783	0.0027	8784	N.A.	8785	N.A.	37.04
	8790	0.0048	8791	N.A.	8792	N.A.	20.83
	8797	0.0037	8798	N.A.	8799	N.A.	27.03
111	8748	0.0068	8749	0.0059	8750	0.0055	14.71
	8755	0.0065	8756	0.0055	8757	0.0049	15.38
	8762	0.0047	8763	0.0044	8764	0.0046	21.28
	8769	0.0070	8770	0.0060	8771	0.0053	14.29
	8776	0.0059	8777	0.0053	8778	0.0046	16.95
	8783	0.0034	8784	0.0025	8785	0.0019	29.41
	8790	0.0062	8791	0.0048	8792	0.0041	16.13
	8797	0.0051	8798	0.0038	8799	0.0032	19.61

Table 4.7
Summary of Expanded Tube Stresses

Case	Tubesht - TSP C		TSP C - TSP F		TSP F - TSP J		Pressure Load to Cause Expanded Tube to Yield (psi)
	Element	Tube Stress (psi)	Element	Tube Stress (psi)	Element	Tube Stress (psi)	
102	Not Applicable						
103	Not Applicable						
112	8745	2325.0	8746	N.A.	8747	N.A.	15.18
	8752	2518.0	8753	N.A.	8754	N.A.	14.02
	8759	1697.0	8760	N.A.	8761	N.A.	20.80
	8766	2649.0	8767	N.A.	8768	N.A.	13.33
	8773	2320.0	8774	N.A.	8775	N.A.	15.22
	8780	1114.0	8781	N.A.	8782	N.A.	31.69
	8787	1990.0	8788	N.A.	8789	N.A.	17.74
	8794	1534.0	8795	N.A.	8796	N.A.	23.01
111	8745	7569.0	8746	4742.0	8747	2285.0	4.66
	8752	7075.0	8753	4337.0	8754	2046.0	4.99
	8759	5746.0	8760	5771.0	8761	1916.0	6.12
	8766	7696.0	8767	4750.0	8768	2229.0	4.59
	8773	6631.0	8774	4162.0	8775	1942.0	5.32
	8780	3292.0	8781	1862.0	8782	814.0	10.72
	8787	6316.0	8788	3711.0	8789	1697.0	5.59
	8794	5052.0	8795	2921.0	8796	1327.0	6.99

Tube Yield Stress = 35,300 psi

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Table 4.8
Summary of Plate Displacements

Case 102
Plate C Active
Upward Applied Load
Without Tube Expansions

	Displacement Range (inch)									
	0.000 0.008	0.008 0.016	0.016 0.024	0.024 0.032	0.032 0.040	0.040 0.048	0.048 0.056	0.056 0.064	0.064 0.072	0.072 0.081
Number of Tubes	**208**	**478**	**342**	**302**	**250**	**222**	**304**	**171**	**79**	**69**

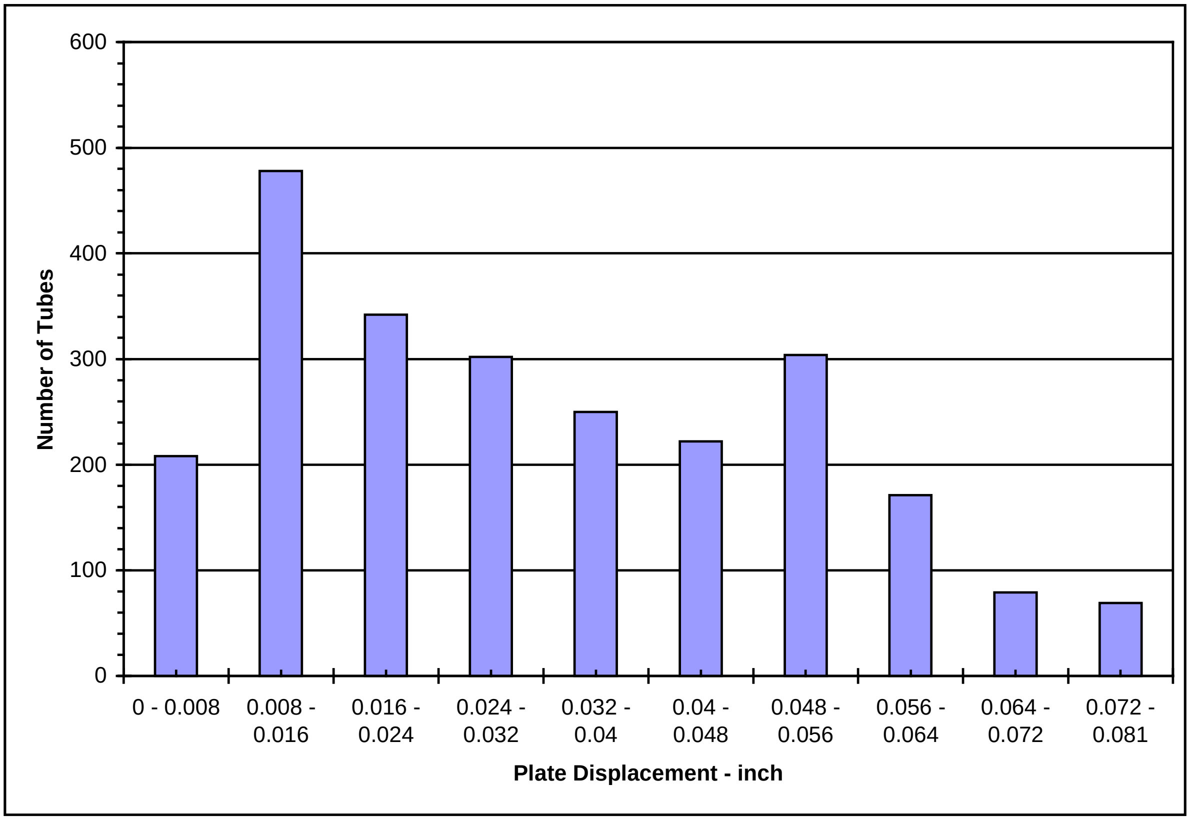

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Table 4.9
Summary of Plate Displacements
Case 103

Plate C Active
Downward Applied Load
Without Tube Expansions

	Displacement Range (inch)									
	0.000 0.006	0.006 0.011	0.011 0.017	0.017 0.022	0.022 0.028	0.028 0.034	0.034 0.039	0.039 0.045	0.045 0.050	0.050 0.057
Number of Tubes	**556**	**409**	**371**	**226**	**274**	**245**	**198**	**48**	**50**	**44**

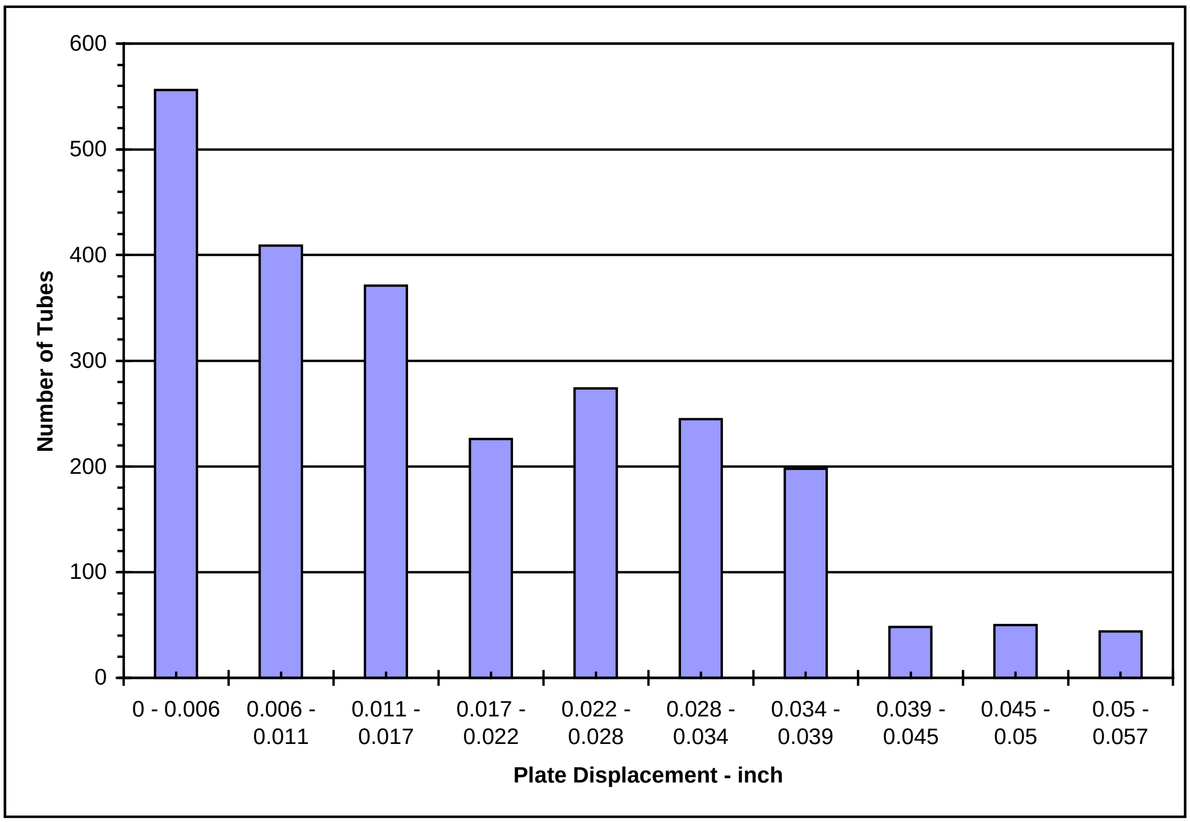

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Table 4.10
Summary of Plate Displacements
Case 112

Plate C Active
Upward Applied Load
Eight Tube Expansions (Hot Leg – Half Bundle)

	Displacement Range (inch)									
	0.000 0.001	0.001 0.003	0.003 0.004	0.004 0.006	0.006 0.007	0.007 0.008	0.008 0.010	0.010 0.011	0.011 0.013	0.013 0.014
Number of Tubes	**0**	**30**	**122**	**217**	**216**	**450**	**404**	**556**	**368**	**62**

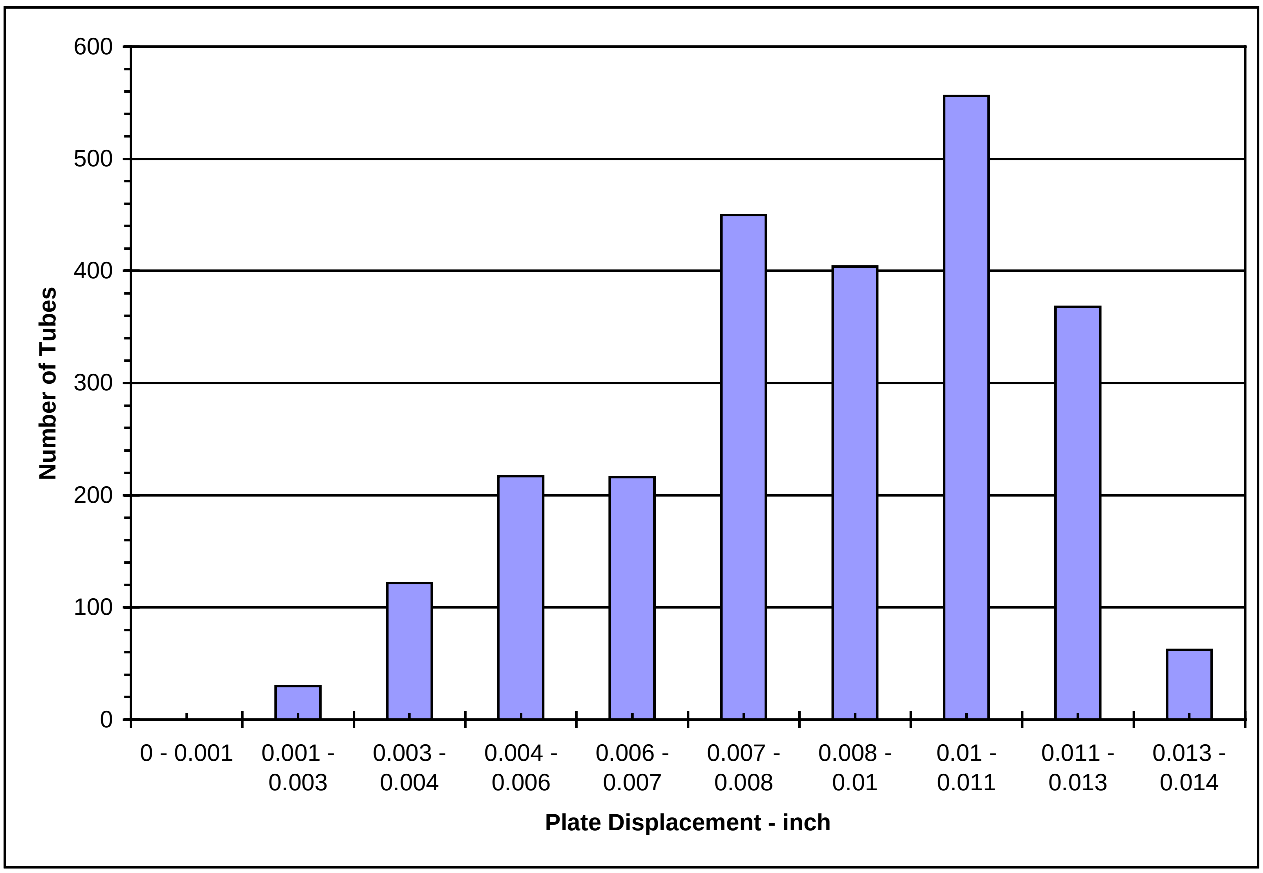

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Table 4.11
Summary of Plate Displacements
Case 111

Plates C, F, and J Active
Upward Applied Load
Eight Tube Expansions (Hot Leg – Half Bundle)

Plate C

	Displacement Range (inch)									
	0.000 0.002	0.002 0.005	0.005 0.007	0.007 0.010	0.010 0.012	0.012 0.014	0.014 0.017	0.017 0.019	0.019 0.022	0.022 0.024
Number of Tubes	**2**	**66**	**144**	**185**	**247**	**276**	**437**	**625**	**250**	**193**

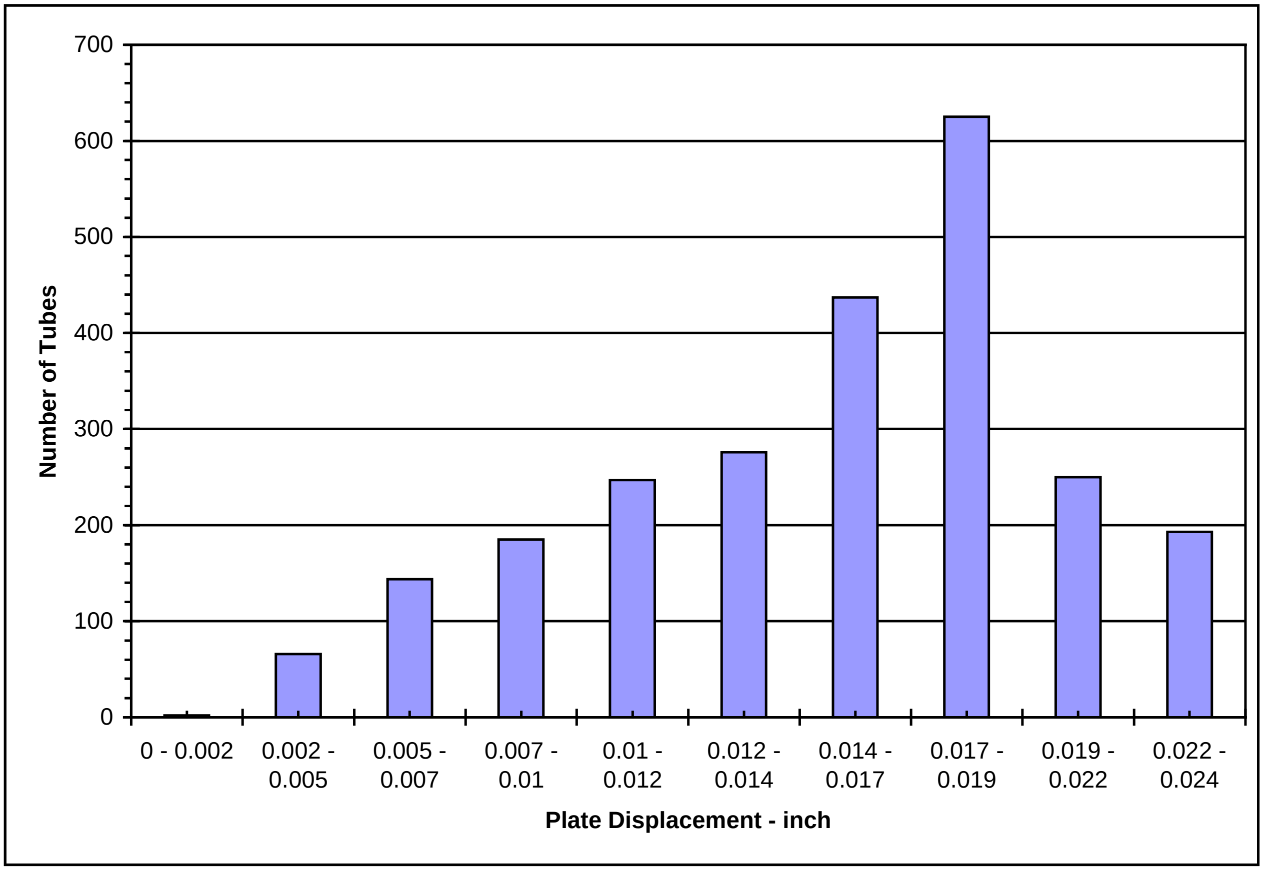

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Table 4.12
Summary of Plate Displacements
Case 111

Plates C, F, and J Active
Upward Applied Load
Eight Tube Expansions (Hot Leg – Half Bundle)

Plate F

	Displacement Range (inch)									
	0.000 0.003	0.003 0.005	0.005 0.008	0.008 0.010	0.010 0.013	0.013 0.015	0.015 0.018	0.018 0.020	0.020 0.023	0.023 0.025
Number of Tubes	**2**	**62**	**141**	**193**	**209**	**243**	**299**	**351**	**395**	**530**

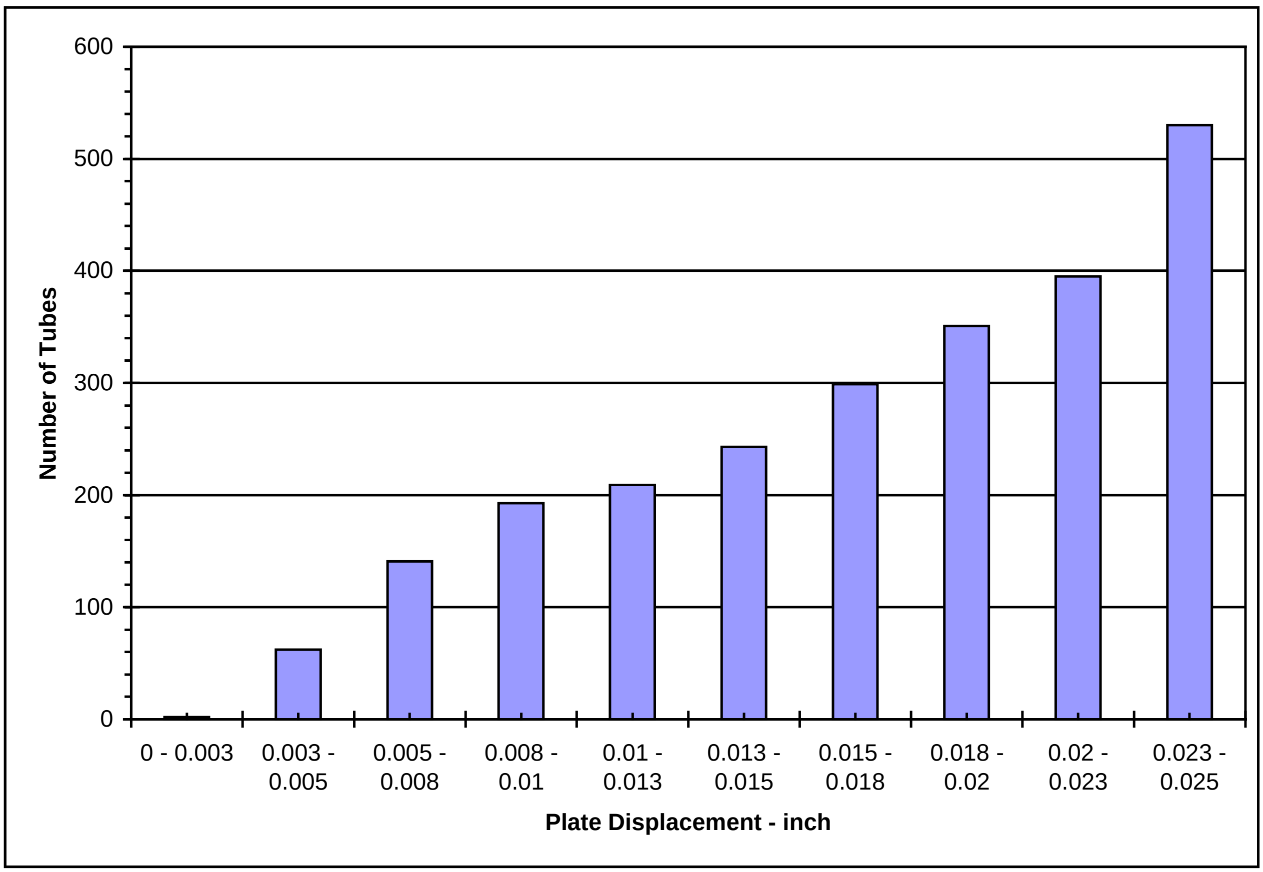

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Table 4.13
Summary of Plate Displacements
Case 111

Plates C, F, and J Active
Upward Applied Load
Eight Tube Expansions (Hot Leg – Half Bundle)

Plate J

	Displacement Range (inch)									
	0.000 0.003	0.003 0.006	0.006 0.008	0.008 0.011	0.011 0.014	0.014 0.017	0.017 0.020	0.020 0.022	0.022 0.025	0.025 0.028
Number of Tubes	**4**	**94**	**186**	**225**	**252**	**283**	**330**	**336**	**382**	**333**

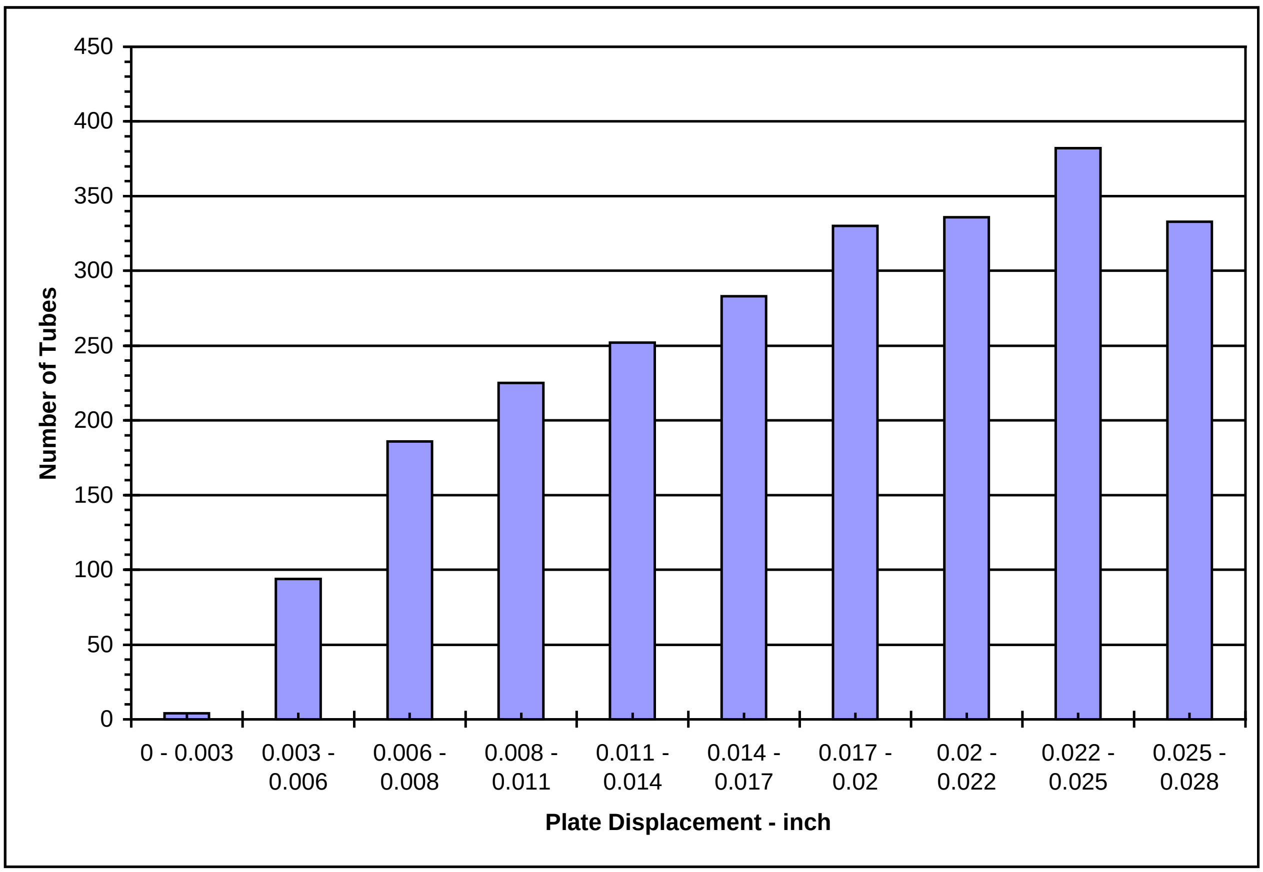

Table 4. 14
Summary of Factors of Safety for Applicable Criteria

Case	Applied Load (psi)	Noumber of Tube Expansions	Unit Load Max Displacement (inch)	ΔP to Reach 0.30" Displacement		ΔP to Reach TSP Yield		ΔP to Reach Stayrod/Spacer Yield		ΔP to Reach 0.1" Expansion Extension		ΔP to Reach Expanded Tube Yield	
				ΔP (psi)	Factor of Safety (1)	ΔP (psi)	Factor of Safety (1)	ΔP (psi)	Factor of Safety (1)	ΔP (psi)	Factor of Safety (1)	ΔP (psi)	Factor of Safety (1)
102	1.0	0	0.0808	3.71	1.04	3.55	1.00	31.95	8.98	NA	NA	NA	NA
103	-1.0	0	-0.0565	-5.31	2.27	-3.44	1.46	-26.74	-7.51	NA	NA	NA	NA
112	1.0	16	0.0135	22.17	6.23	14.25	4.00	94.18	26.46	15.87	4.46	13.33	3.74
111	1.0 (C)	16	0.0240	12.52	3.52	12.11	3.40	37.40	10.51	14.29	4.01	4.59	1.29
(2)	1.0 (F)		0.0254	11.80	3.31	13.56	3.81						
	1.0 (J)		0.0282	10.64	2.99	10.76	3.02						

(1) - Maximum upward pressure drop = 3.56 psid; maximum downward load = -2.346 psid; Ref. Section 3

(2) - Plates C, F, and J loaded simultaneously

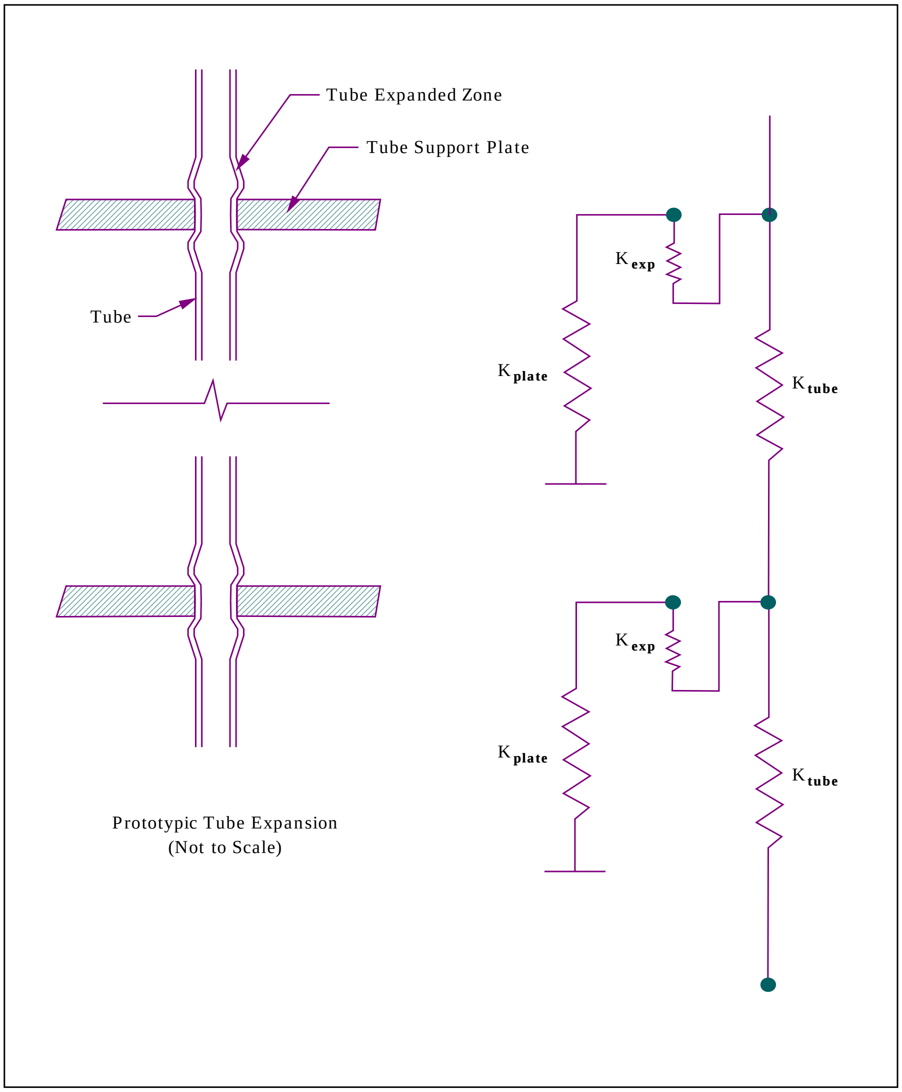

Figure 4.1
Model Representation of
Expanded Tube / Sleeve / Tubesheet Interface

a,c

Figure 4.2
Expanded Tube Location