3.0 THERMAL/HYDRAULIC ANALYSIS

3.1 Steam Line Break Characteristics

A schematic of a Westinghouse Model E steam generator is shown in Figure 3-1. The steam generator utilizes a venturi flow restrictor in the main steam line nozzle to limit the magnitude of the break flow during a steam line break accident. In the top of the steam generator just below the steam line nozzle, there are several open volumetric regions in the flow paths with cross-sectional areas that vary between 75 times and 145 times the size of the flow area of the flow restrictor. These large flow areas act as accumulators that tend to absorb pressure fluctuations from the steam line and result in relatively low steam velocities near the top of the steam generator inside the main steam nozzle. In addition, there are two sets of steam separators that the steam flow must pass through prior to entering the steam outlet nozzle. These steam separators act in series and provide resistance to the steam flow as it approaches the main steam nozzle.

The water in the steam generator resides primarily in the region below the primary separators. When the steam generator is operating at power, the water in most of the tube bundle region is a two-phase mixture of steam and water with increased quality in the higher regions of the tube bundle. Typically, subcooled water will be present in the preheater section of the bundle with slight subcooling in the lower regions of the bundle just above the tube sheet depending on the operating power level. The flow in the bundle region will be upwards due to natural convection effects arising from differences in density between the two-phase fluid in the heated tube bundle and the single phase fluid in the unheated downcomer. The flow in the tube bundle is upwards and two-phase. Almost all the liquid entrained in the flow leaving the tube bundle is separated by gravity in the steam separators and is returned to the bundle via the downcomer annulus. The ratio of the total flow in the bundle to the steam flow escaping the main steam nozzle is known as the circulation ratio and is about 2.35 (Ref. Section 4.3, WCAP 15163, Rev 1) for the Model E steam generator when it is operating at full power. Consequently, at full power operating conditions the upward flow in the tube bundle is about 2.35 times the steam flow that exits the main steam nozzle. Under these operating conditions, the largest pressure drop across a tube support plate is less than 1 psid.

When a steam line break occurs from full power operating conditions, the flow from the steam nozzle increases by about a factor of 3 until the flow restrictor chokes. Due to the resulting flow imbalance, a depressurization of the large volume at the top of the steam generator occurs. The decrease in pressure acts to disrupt the circulation flow as the flow in the downcomer slows down and reverses to help supply the flow to the break. Consequently, when a steam line break occurs from full power operating conditions, there will be only a moderate increase in flow in the bundle itself that is directly attributable to the break. However, there is a secondary, more substantial contribution to flow in the tube bundle caused by the swelling of the fluid in the tube bundle region due to flashing as the steam generator pressure decreases. This swelling effect in the tube bundle generates the peak loads on the tube support plates during the early part of a steam line break. Since the tube bundle region already contains substantial voids when the steam generator is operating, the surge associated with swelling in the tube bundle from a steam line break from hot standby conditions will result in the worst case tube support plate loads for the steam generator.

3.2 Methods

To determine the peak loads that could occur during a steam line break, a simplified calculation was employed to estimate the peak loads on the tube support plates that would occur as a result of the surge associated with depressurization of the steam generator due to a steam line break. This simplified method utilizes a mass and energy balance of the fluid contained within the tube bundle region of the steam generator to determine the volumetric swell that would occur as a result of depressurization due to the postulated break. Since the increased volume must be removed from the bundle region as flow through the tube support plates, the calculation can be used to determine the flow across each tube support plate and the resulting load that will be applied. The technique employed and the results obtained are discussed in Section 3.3 below.

In addition to considering the loads on the tube support plates that result from the relatively steady depressurization of the steam generator associated with the steam line break, the effect that pressure fluctuations in the steam line would have on the internals in the tube bundle was also investigated. These results are discussed in Section 3.4 below.

3.3 Simplified Analysis for Peak Loads due to Swell

During hot standby conditions, the tube bundle region will contain stagnant, essentially saturated, water slightly subcooled with depth due to the gravitational head from the water level. When a steam line break occurs, the steam generator will begin to depressurize and the hot water in the tube bundle will begin to flash. This results in a sudden swell that forces the fluid in the tube bundle to expand through the tube support plates. There are two exit paths from the tube bundle that the expanding fluid can take. The fluid can escape by flowing up through the U-bends and into the primary separators or it can escape by flowing down towards the tubesheet and up the downcomer annulus. The ratio of the flow for these two escape paths will depend on the relative resistances involved.

Since the flow will escape the tube bundle in two opposite directions, there will be a stagnation region located at a particular height in the tube bundle where the flow will be very small. The fluid above this stagnation region will go up towards the U-bends whereas the fluid below this stagnation region will go down towards the tubesheet and up through the downcomer. By making conservative assumptions regarding the escape flow path, conservative values for the peak pressure drops across each tube support plate can be obtained once the magnitude of the volumetric expansion is defined.

3.3.1 Assumptions

The load on a particular tube support plate will result from the accumulation of flow from the expansion of all the fluid between the stagnation region and that tube support plate. Therefore, an assumption that the stagnation region is too low will result in conservative loads on the upper tube support plates and non-conservative loads for the lower support plates. Similarly, an assumption that the stagnation region is too high will result in conservative loads on the lower tube support plates and non-conservative loads on the upper tube support plates. The assumptions used for this simplified analysis are summarized below:

- Homogeneous equilibrium conditions are assumed for the analysis. The assumption of equilibrium conditions results in instantaneous flashing in reaction to a drop in pressure and will overestimate the rate of fluid expansion. In addition, the assumption of homogeneous flow will limit the ability of the steam to escape from the tube bundle and will also result in an overestimate of the expansion.

- For estimating the load on the upper tube support plates, it is assumed that the flow path through the downcomer is blocked. For this case, all the expansion of fluid in the tube bundle is forced upwards through the tube support plates.

- For estimating the load on the lower tube support plates, it is assumed that only half the flow expands up through the U-bends. The increased resistance associated with obstruction of flow by the preheater in the cold leg and the flow path up the downcomer is significantly higher than that for flow up through the U-bends so the flow stagnation region will be lower in the bundle than assumed here. Requiring that all the flow due to expansion go up the downcomer would be overly conservative.

- All resistance in flow between the tube bundle and the main steam outlet nozzle is ignored. This is conservative as it overestimates the pressure at the nozzle that results in an overestimate of the break flow. The effect is small early in the transient when the highest tube support loads are calculated.

3.3.2 Method

The steam generator is assumed to be at hot standby conditions (1200 psia stagnant saturated steam and water) and is divided into upper and lower regions. The upper region includes the part of the steam generator that is above the water level and includes only saturated steam. The lower region includes the part of the steam generator that is below the water level and initially includes only saturated water.

Based on the initial conditions, the total mass and energy are determined for each region using the properties for saturated steam and water from the ASME steam tables and the initial volumes of each region.

$$M = V / v$$

$$U = M (h - P v)$$

Where: M is the total mass in each region
U is the total energy in each region
V is the volume of the region
v is the specific volume from the steam tables
h is the specific enthalpy from the steam tables
P is the pressure

When the steam line break occurs, the flow at the break is determined from the critical mass flux for saturated steam as a function of pressure as provided by the ASME steam tables. For a particular time step, the mass and energy in the upper region will be reduced as a result of flow out the steam nozzle:

$$\Delta M = - W_{crit} \, \Delta t$$

$$\Delta U = - h \, W_{crit} \, \Delta t$$

where: W_{crit} is the critical mass flow from the break
Δt is the time step

The mass and energy of the lower region are unchanged as the boundary of this region is selected such as to contain the original mass. This requires that the lower region expand and the upper region contract to maintain pressure equilibrium between the two regions. An iterative technique is employed to obtain the appropriate volumes for the upper and lower regions that maintain the total volume constant and result in the pressures in the two regions being the same. As a result, vapor will be formed in the lower region since the specific volume increases but the total mass remains constant. Once the new volume of the lower region is determined, a new specific volume for the expanded fluid in that region can be calculated.

As a result of the reduced pressure and the expansion of fluid in the lower region, the volume of the steam generator between the tubesheet and the top tube support plate will lose mass.

$$\Delta M_B = V_B(t+\Delta t)/ v_B(t+\Delta t) \quad - V_B(t)/ v_B(t)$$

where:
- M_B is the mass in the bundle between the tubesheet and the upper tube support plate
- V_B is the volume in the bundle between the tubesheet and the upper tube support plate
- v_B is the specific volume in the bundle between the tubesheet and the upper tube support plate

The rate of change of mass in the tube bundle from one time step to the next provides a measure of the total flow leaving the tube bundle during the time step.

$$W_B = \Delta M_B/\Delta t$$

By making conservative assumptions regarding the path that this flow must take as it flows out of the tube bundle region, a conservative measure of the pressure drop on each tube support plate can be obtained.

$$\Delta P = K\, W^2 / (\rho\, A^2)$$

where:
- K is the loss coefficient for the tube support plate based on the flow area through the plate
- W is the portion of the mass flow rate that passes through the tube support plate
- ρ is the density of the fluid flowing through the plate
- A is the flow area through the plate

For example, if one assumes that all the flow from expansion of the fluid in the tube bundle must flow upwards, the top tube support plate must pass all the flow while the bottom tube support plate will only pass the expanded flow from the region below it. Consequently, the load on the top tube support plate will be conservatively overestimated for this assumption while the load on the bottom tube support plate may be underestimated.

3.3.3 Results of Simplified Analysis

The technique described above was employed to obtain a conservative estimate of the loads that would occur on the tube support plates of the model E steam generator as a result of a steam line break. The technique was programmed for a personal computer using computerized steam tables. Parameters used for the analysis are summarized in Table 3.1.

The results indicate that for the conservative equilibrium assumption, the peak pressure drops for the tube support plates occur when flashing in the tube bundle initiates. Voids already present in the tube bundle region act to reduce the expansion effect associated with further pressure decreases so the calculated loads on the tube support plates diminish with time for a constant depressurization rate.

In order to obtain conservative results for all tube support plates, three separate assumptions on flow distribution were employed. The results of these analyses are summarized in Table 3.2 and are discussed below.

For the first case, it was assumed that no flow can escape up the downcomer and all flow must pass up through the tube bundle. This assumption provides conservative results for the upper tube support plates as they experience the full expansion flow, some of which would normally escape up the downcomer.

The second case assumed that half the flow escapes upwards through the tube bundle and half the flow escapes through the downcomer. Due to the higher resistance for the flow path through the downcomer, the tube bundle flow will necessarily be higher than the downcomer flow so the assumption of an equal flow split is conservative for calculating the pressure drops for the lower tube support plates.

Assuming the full flow escapes through the downcomer in a manner opposite to that used for Case 1 will result in overly conservative results for the lower tube support plates. Nevertheless, this case was also run as Case 3 and is included in the results in Table 3.2. The pressure drops that were obtained for the lower tube support plates for Case 3 are very high when compared to those for the upper tube support plates from the comparable Case 1. This confirms that the path of least resistance would be out the top of the tube bundle and helps justify that Case 2 results are conservative for the lower tube support plates.

For the sake of comparison, Table 3.2 also includes the results obtained from the analysis from hot standby conditions using the RELAP program.

Figures 3-2 through 3-5 provide plots of the calculated results for the first two seconds of the simplified transient analysis. Figure 3-2 shows the pressure inside the steam generator which is calculated from the remaining mass and energy existing inside the steam generator at each time step as previously discussed in Section 3.3.2. The calculated critical mass flow rate at the nozzle is shown in Figure 3-3 and was determined from the calculated pressure using the data from the ASME steam tables. Saturated steam was assumed at the nozzle location as little moisture will reach the nozzle until after the swell inside the steam generator is high enough to flood the steam separators.

Figure 3-4 shows the calculated volumes for the upper (steam only) region of the steam generator and the lower (two-phase mixture) region of the steam generator as utilized for the iterative pressure calculation. When the volume of the upper region that contains only steam disappears, moisture will arrive at the nozzle and the critical mass flow rate will increase due to increased fluid density. However, the pressure drop across the tube support plates due to the swell of the fluid will be significantly reduced by this time.

Figures 3-5 shows the calculated flow rate that must be removed from the volume beneath the top support plate as a result of the expansion of the fluid due to the depressurization. The mass flow due to swell that occurs early in the transient is almost an order of magnitude higher the critical mass flow at the break. The manner in which this flow is distributed between up-flow and down-flow determines the load on each tube support plate.

3.4 Effect of Steam Line Pressure Fluctuations

The effects of a steam line break will diminish with time as the steam generator depressurizes and the flow out the break decreases. As long as the pressure in the steam generator is high enough and the break large enough to choke the flow restrictor in the steam outlet nozzle, pressure fluctuations in the steam line downstream of the nozzle will not be able to propagate into the steam generator. If the area of the break is small enough (less than about 0.45 square feet or about 1/3 of the area of the flow restrictor), the break flow will be less than that normally experienced during operation. The internals of the steam generator should not be significantly affected since there is considerable operating experience at this level of flow. Nevertheless, it may be possible that for a medium sized break for which the break area is smaller than the nozzle area, the break flow could exceed the full power operating flow and the flow restrictor could not be choked. Under these conditions, pressure fluctuations in the steam line could possibly propagate into the steam generator and affect the internals. Nevertheless, the significant change in area and the presence of the compressible steam in the large volume at the top of the steam generator combine to act as an accumulator and will help to isolate the lower internals from the effect of sudden pressure changes in the steam line.

Additional isolation for the tube bundle region is provided by significant resistance that exists across the two levels of steam separators and the presence of large amounts of saturated liquid that can flash to maintain the pressure near saturation pressure. As a result, any sudden depressurization in the steam line leads to a much slower depressurization of the steam generator as a whole and relatively small pressure gradients would be expected inside the tube bundle. The pressure gradients that are established are primarily a result of “steady flow” rather than dynamic imbalance due to flow acceleration. In fact, the dominant loads on the tube support plates in the tube bundle result from the swell of the fluid trapped by the support plates as the steam generator begins to depressurize rather than from the propagation of sonic waves from the main steam nozzle.

To estimate the extent to which pressure fluctuations in the steam line could propagate into the tube bundle of the steam generator, a two-phase thermal-hydraulic analysis was conducted for which a sinusoidal pressure oscillation was imposed at the steam line boundary. The steam generator was assumed to be at hot standby. The pressure response in the tube bundle region was determined as a function of the applied oscillatory pressure in the steam line. The analyses were run until steady state oscillating conditions were achieved. Several such analyses were conducted using several different frequencies for the pressure oscillations to determine the frequency transform for the pressure oscillations between the steam line and the tube bundle region.

3.4.1 Method

The steam generator was divided into control volumes that contain mass and energy. The control volumes are connected together by fluid connectors that transfer mass and energy between the control volumes. The integrated form of the momentum, mass, and energy conservation equations were solved for the control volumes and connectors to obtain transient pressures and flows. Computerized steam tables were used to represent the properties of the fluid and rigorous mass and energy conservation was imposed. Results from the technique have been compared to analytic solutions for wave propagation in piping systems with good agreement.

3.4.2 Results

Results obtained from five separate runs with pressure oscillation frequencies between 10 and 50 Hertz are summarized in Table 3-3 and are plotted in Figure 3-6. These results provide the relative amplitude of the calculated response of pressure at the inside of the steam nozzle, at the top of the tube bundle, and at the region just above the tubesheet as compared to the amplitude of the pressure oscillations imposed at the steam line boundary. At low frequency, the calculated amplitude of the pressure oscillations at the tubesheet is about 7 per cent of the amplitude of the applied pressure oscillations in the steam line whereas the amplitude of the pressure oscillations at the U-bends is about 2 per cent of the applied amplitude. There appears to be some frequency dependence for the response at low frequencies, particularly near the steam nozzle. This may indicate an acoustic resonance effect at the top of the steam generator since the response is about 90 degrees out of phase with the applied pressure. However, the response in the tube bundle remains low for all the analyzed frequencies. For frequencies above 30 Hertz, the calculated response in the tube bundle is negligible.

Figures 3-7, 3-8, and 3-9 show the detailed transient pressures for the 10 Hertz, 30 Hertz, and 50 Hertz cases, respectively. At low frequency, there is distortion of the signal between the applied pressure and the response. This may be due to resistances in the flow paths that tend to generate reflections in the pressure signal. These distortions disappear at the higher frequencies analyzed.

Figure 3-10 shows the calculated oscillating pressures at several elevations in the hot leg region for the 20 Hertz analysis case. The peak-to-peak amplitude of the pressure oscillations is about 6 psi for an applied peak-to-peak magnitude in the steam line of 100 psi. The pressures at the different elevations in the hot leg oscillate in phase and the difference in pressure observed in the plot is primarily due to differences in elevation head. Consequently, there is little load on the tube support plates associated with these oscillations.

A further indication that the pressure oscillations apply little load to the tube support plates is provided by Figure 3-12 which shows the calculated flow in the tube bundle region associated with these pressure oscillations. In the figure, W38 is the total flow just above the divider plate and represents the flow through the full tube support plate whereas W39 is the total flow at the top of the hot leg that includes only half the steam generator cross sectional area. The amplitude of the flow oscillations is less than 200 lbs/sec and corresponds to a flow velocity through the minimum area of the support plates of less than 0.25 feet per second. This flow amplitude would be imposed on top of the flow in the tube bundle from the steam line break that was calculated previously to be in the order of 20,000 lbs/sec. Since the loads on the tube support plates vary by the square of the flow rate, the loads on the tube support plate generated by pressure oscillations in the steam line will be negligible when compared to those generated by the steam line break. This would be true even if the amplitude of the pressure oscillations in the steam line is well in excess of the 100 psi peak-to-peak value used for this analysis.

TABLE 3.1
Parameters used for Simplified Analysis

Input Parameter	**Value**	**Comment**
Initial Pressure	1200 psia	Hot Standby Conditions
Total Volume	7585 Cubic Feet	
Water Volume	4500 Cubic Feet	
Flow Area in Bundle	68.1 Square Feet	Full Cross Section
Distance to Top Plate	31.86 Feet	
Break Flow Area	1.338 Square Feet	Area of Venturi
Tube Support Plate	**Flow Area (Square Feet)**	**Resistance Coefficient**
A	9.01	1.23
C	10.45	1.07
F	10.45	1.07
J	8.98	1.17
L	16.83	1.18
M	19.13	1.13
N	19.11	1.13
P	19.13	1.13
Q	19.11	1.13
R	20.99	1.06

TABLE 3.2

Calculated Peak Pressure Drops for Hot Leg Tube Support Plates

Plate	Up-Flow Only (psid)	Split Flow (psid)	Down Flow Only (psid)	RELAP Results (psid)
A	0.013	-5.068	-21.330	-0.97
C	0.139	-2.346	-11.800	-0.88
F	0.534	-1.376	-9.467	-0.66
J	1.756	-0.983	-10.940	-0.71
L	1.011	-0.056	-2.182	0.68
M	1.254	0.003	-1.035	0.63
N	1.893	0.094	-0.583	0.95
P	2.653	0.314	-0.259	1.31
Q	3.553	0.665	-0.068	1.64
R	3.559	0.890	0.000	1.67

TABLE 3.3

Results of Frequency Response Analysis for Pressure Oscillations in Steam Line

Frequency	Relative Response in Per Cent		
	Inside Nozzle	U-Bends	Tubesheet
10	7.2	1.9	6.7
20	4.2	4.9	8.0
30	16.9	0.8	1.1
40	5.5	0.1	0.1
50	3.0	0.05	0.05

DRAFT

Figure 3.1

Model E2 Steam Generator Layout

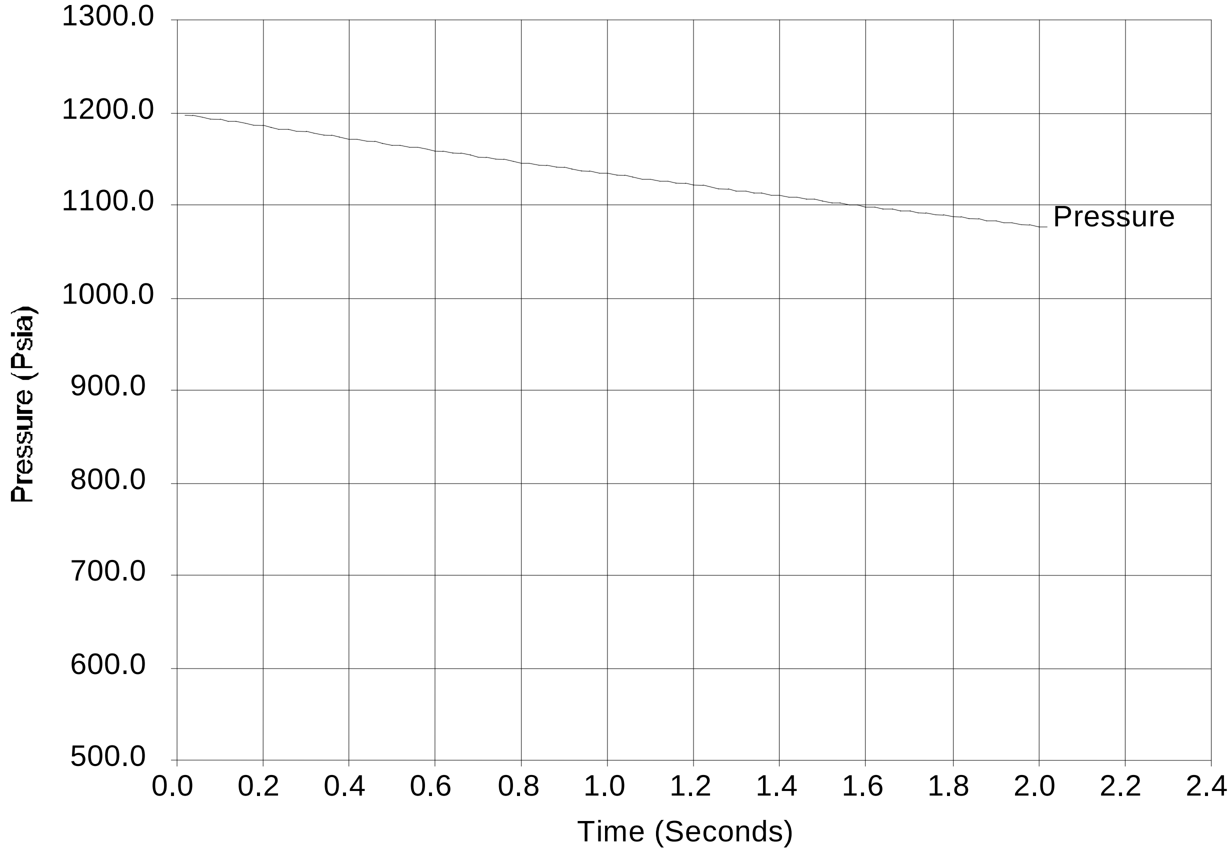
a,c

[

(see figure 3.1, WCAP 15163, Revision 1)

]

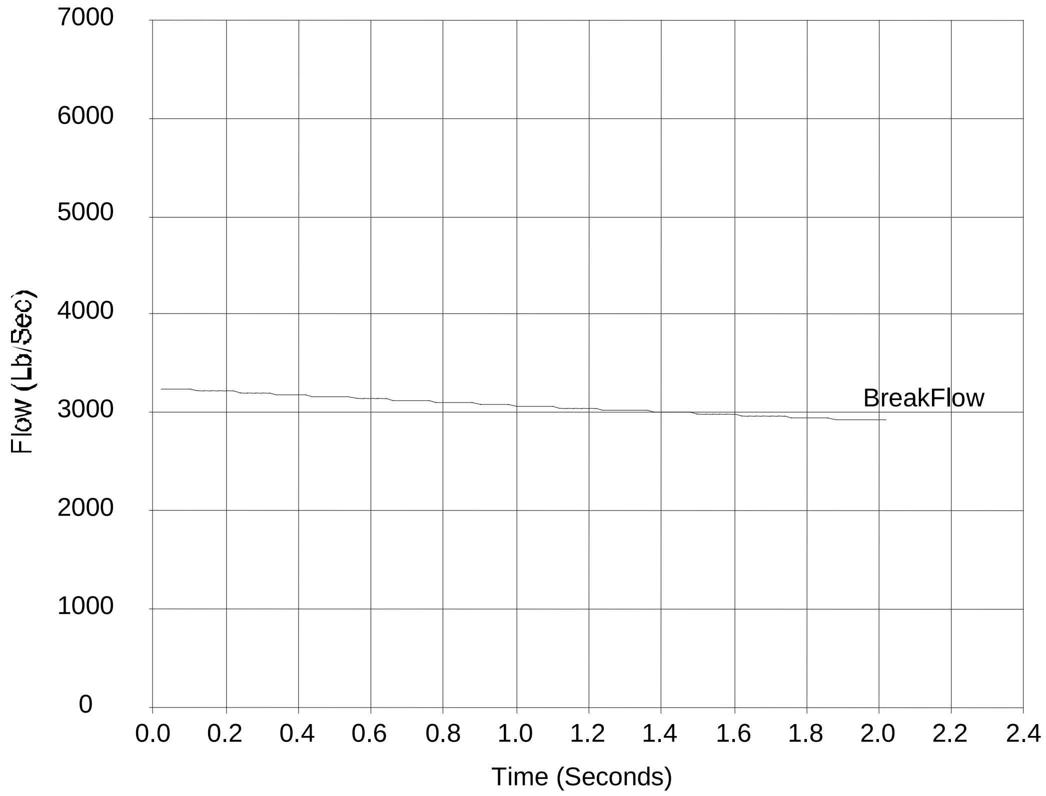
DRAFT



Simplified Conservative Analysis - Calculated Steam Generator Pressure

FIGURE 3-2

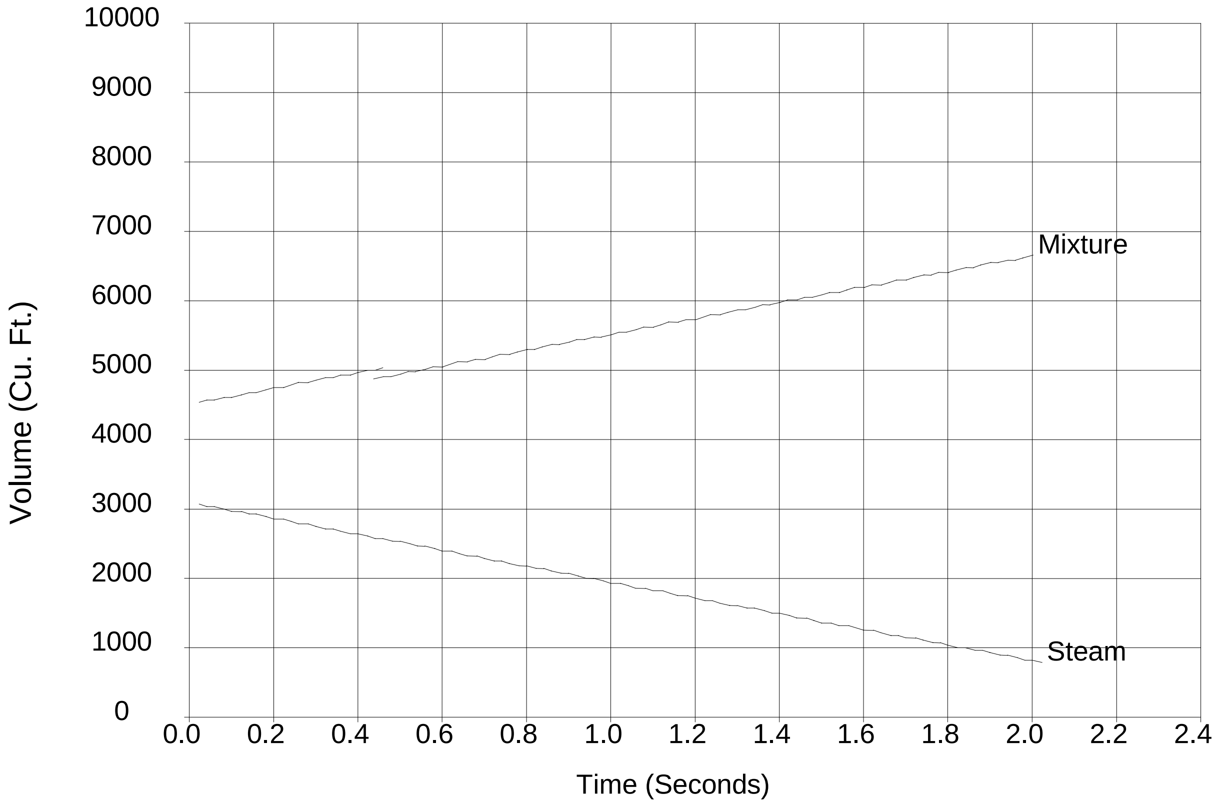
DRAFT



Simplified Conservative Analysis - Calculated Critical Break Mass Flow Rate

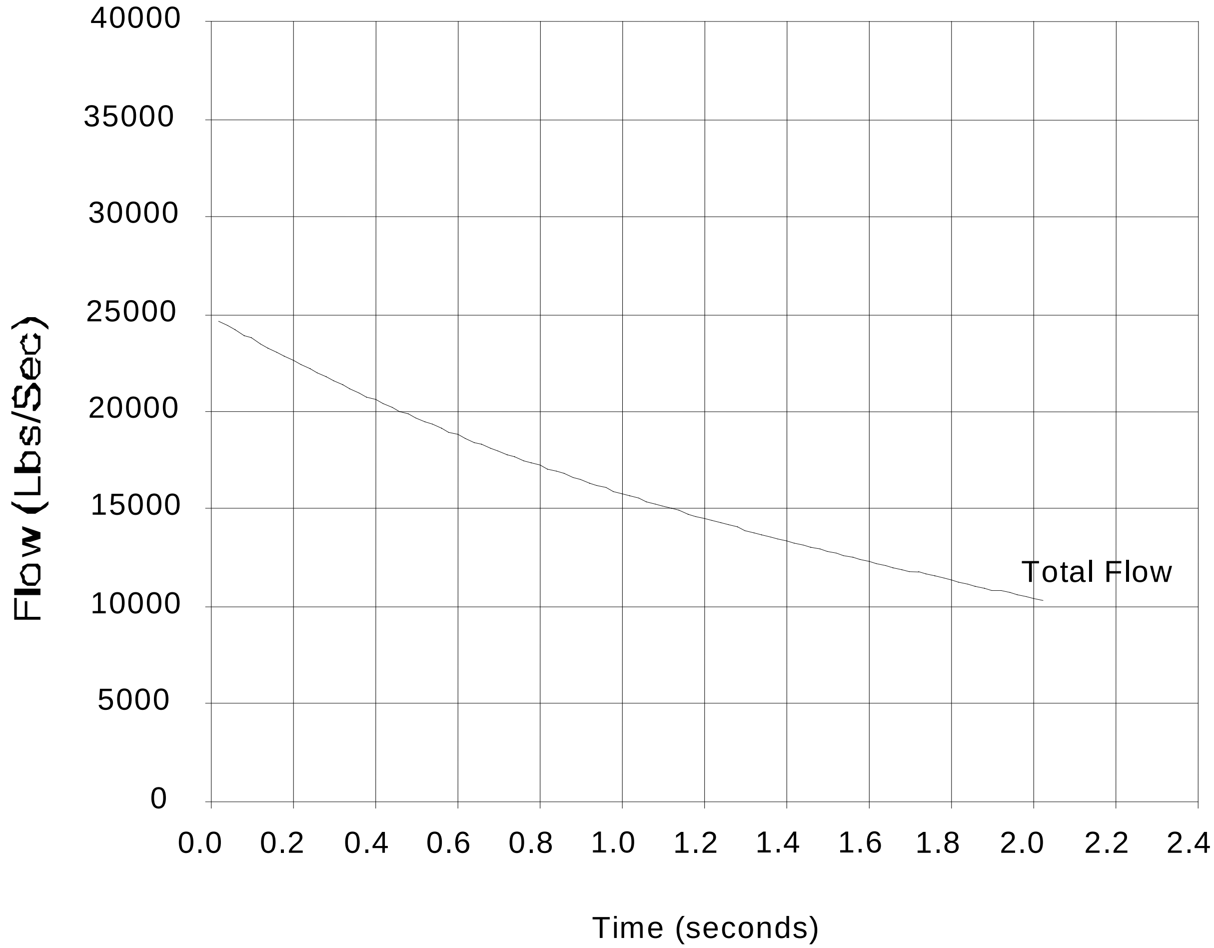
FIGURE 3-3

DRAFT



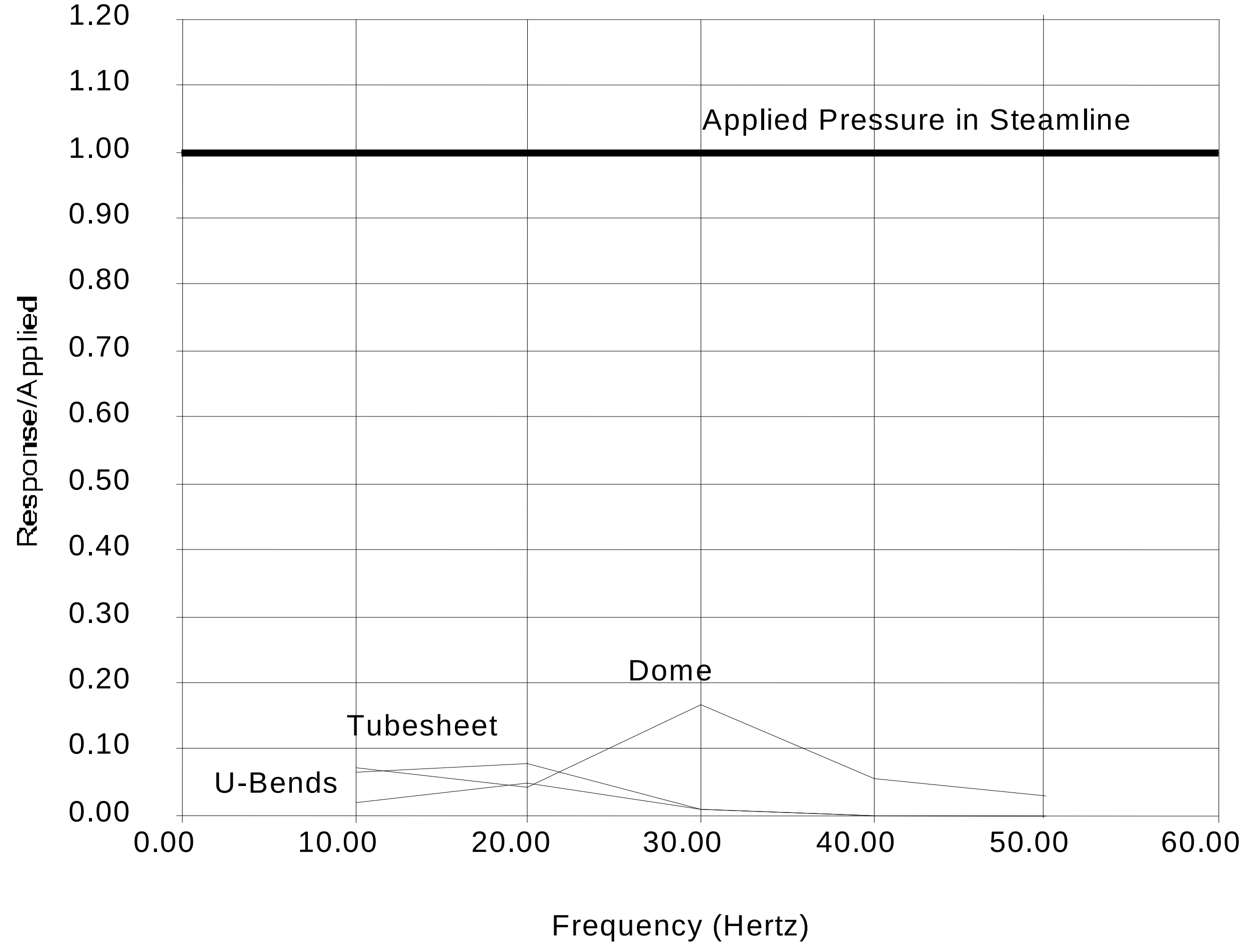
Simplified Conservative Analysis - Calculated Volumes for Regions

FIGURE 3-4



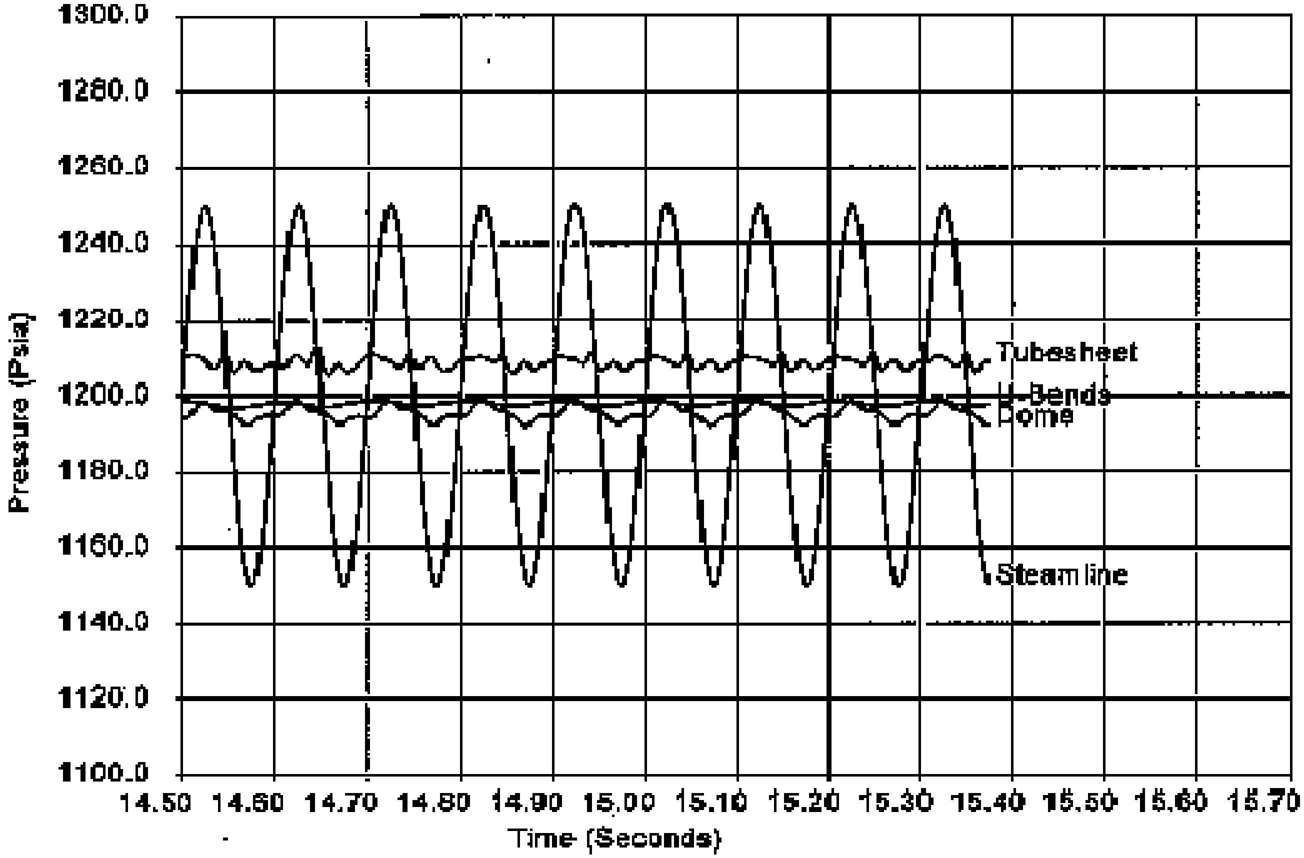
Simplified Conservative Analysis - Total Flow Due to Swell

FIGURE 3-5



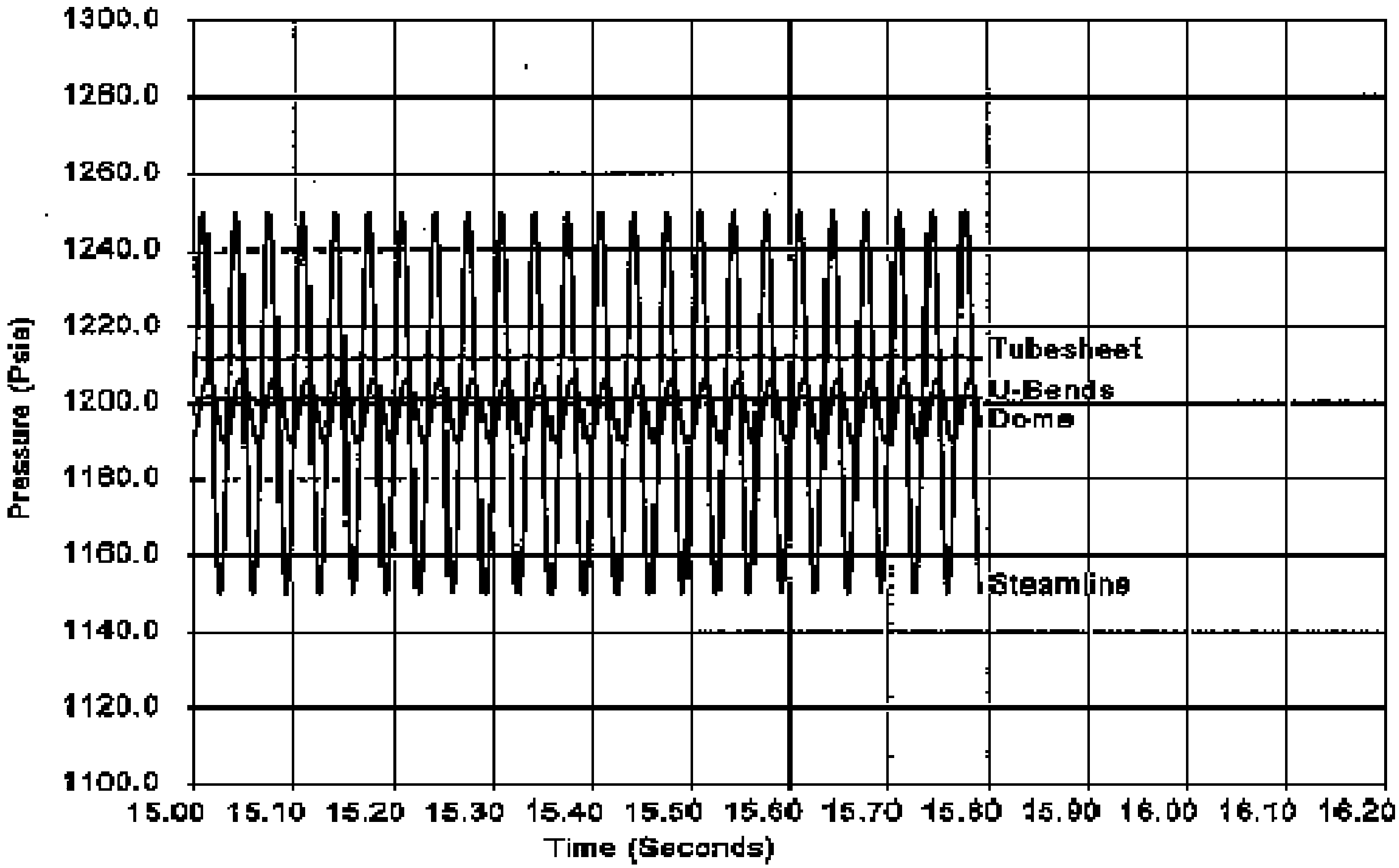
Summary of Results for Steam Line Oscillations at Hot Standby Conditions

FIGURE 3-6



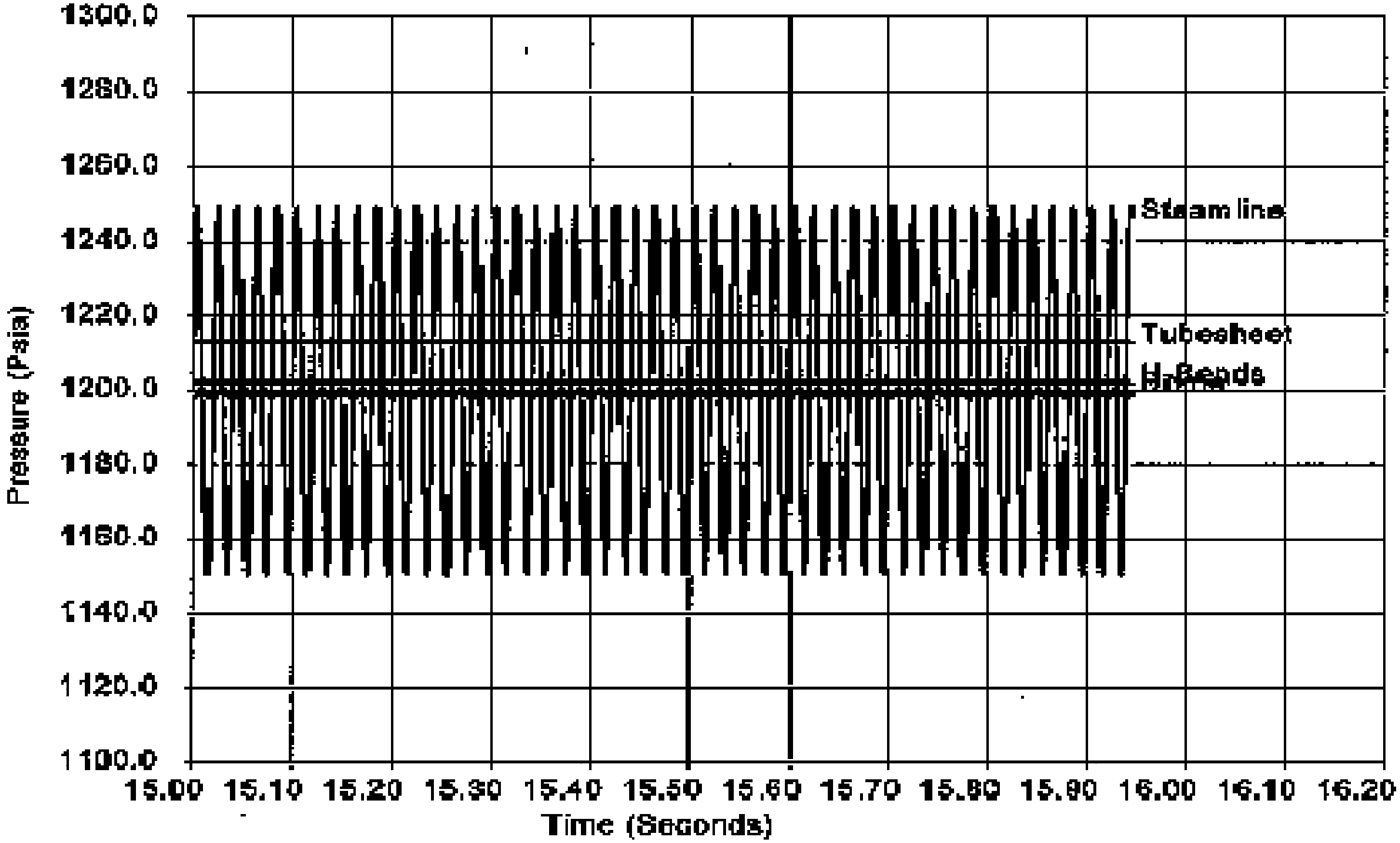
Results at 10 Hertz - Steam Line Oscillations at Hot Standby Conditions

FIGURE 3-7



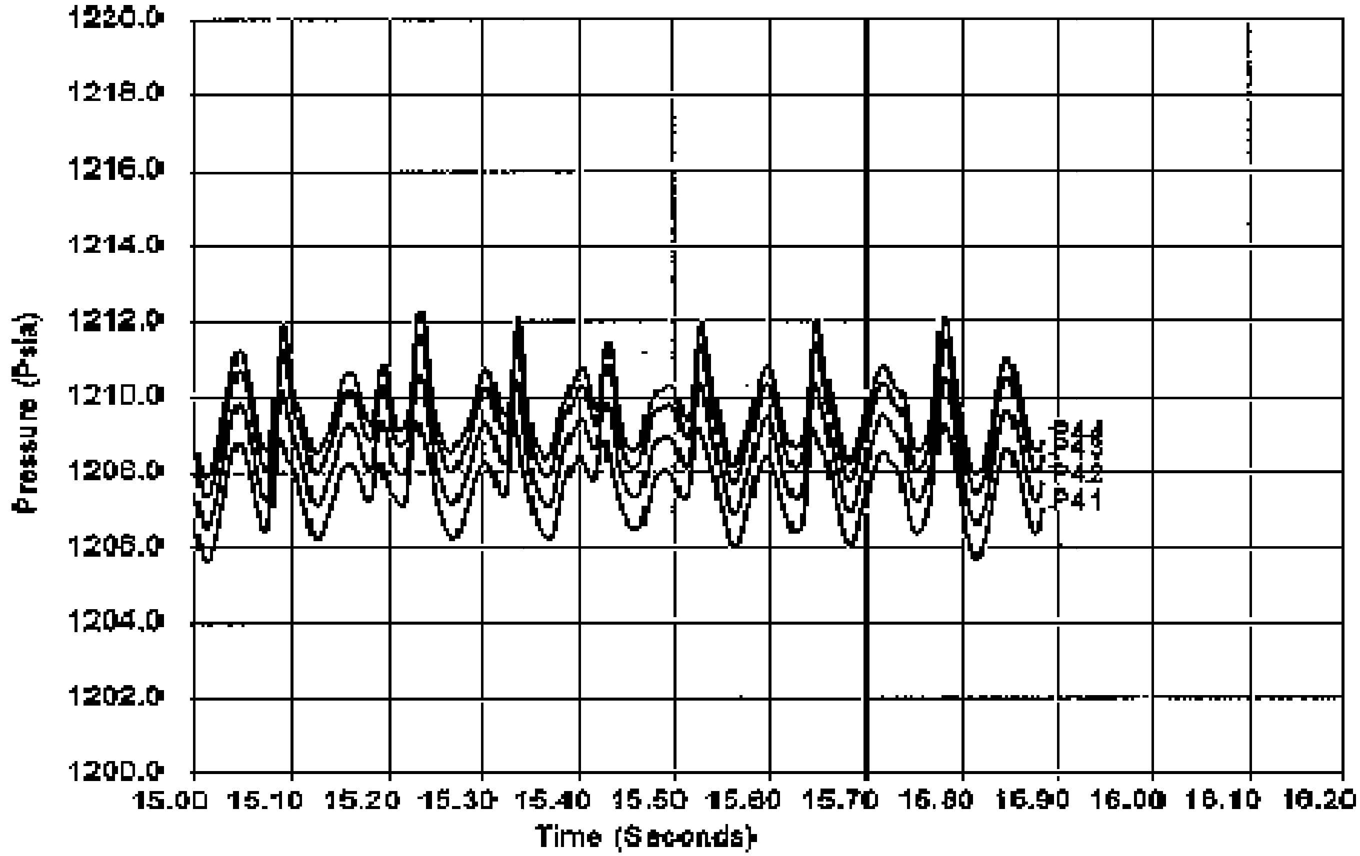
Results at 30 Hertz - Steam Line Oscillations at Hot Standby Conditions

FIGURE 3-8



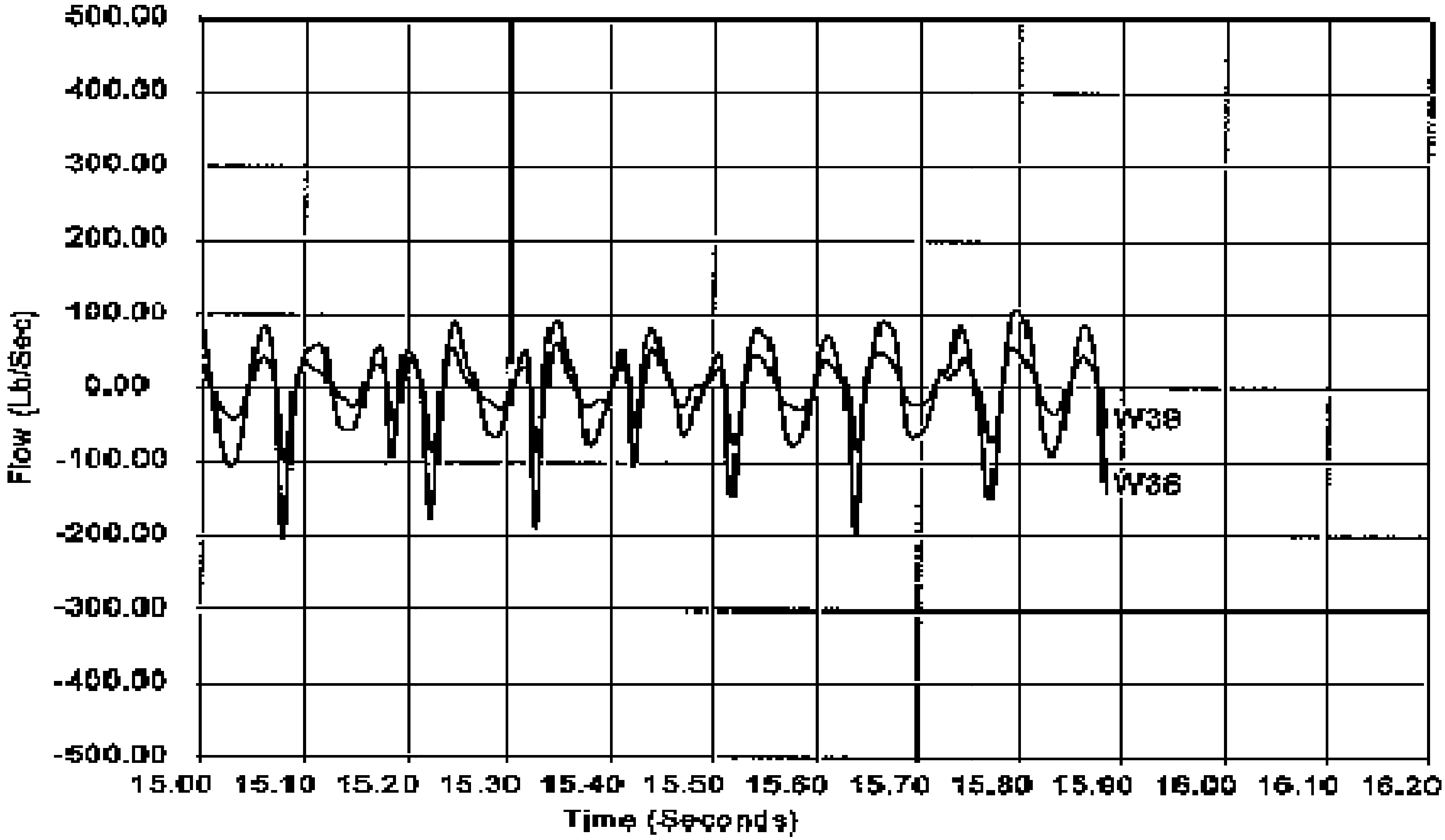
Results at 50 Hertz - Steam Line Oscillations at Hot Standby Conditions

FIGURE 3-9



Results at 20 Hertz - Oscillating Pressures in Hot Leg

FIGURE 3-10



Results at 20 Hertz - Oscillating Flow in Bundle

FIGURE 3-11