분기관 진동에 의한 피로파괴

전 형식*, 박 보용**

(VIBRATION RELATED BRANCH LINE FATIGUE FAILURE)

(Hyong Sik Chun, Bo Yong Park)

INTRODUCTION

Tap lines are small branch piping generally less than two inches in diameter. They typically branch off of header piping having a much larger diameter. An example of a common tap line is a 3/4 inch size high point vent or low point drain. Most tap lines have at least one valve near the header tap connection to provide isolation. Two valves are often required for double isolation.

A light water reactor (LWR) nuclear power plant will have several hundred tap lines. These lines come in many sizes and shapes and serve numerous functions. A single process piping valve may have three different tap lines associated with it (Figure 1). Table 1 delineates the different categories of tap lines.

Vibration failures of tap lines are a common occurrence in all industrial plants including nuclear and fossil power plants. These types of failures constitute a significant percentage of all piping related failures. An unscheduled plant shutdown or outage resulting from the failure of a tap line decreases plant reliability and may have a detrimental effect on plant safety. Most tap line vibration failures can be avoided through the use of appropriate routing and support techniques. Standardized designs can be developed for use in a myriad of applications. These designs will not only minimize failures but will also reduce the necessary analysis and installation efforts.

TABLE 1

SMALL TAP LINE CATEGORIES
. High Point Vents
. Low Point Drains
. Pressure Tap Connections
. Flow Venturi Pressure Tap Lines
. Process Sampling Lines
. Gland Steam Seal Leakoff Lines
. Miscellaneous Instrumentation

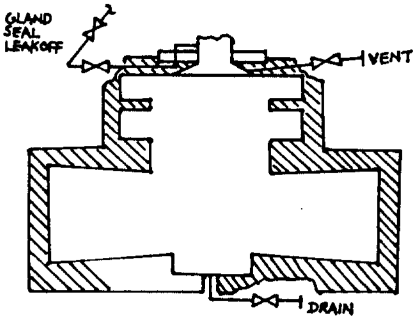

FIG. 1 TAP LINES ASSOCIATED WITH PROCESS PIPING VALVE

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* 신우 기술 (주)

** 인천대학교 기계공학과

PROBLEM IDENTIFICATION

Messrs. Kustu and Scholl performed a survey to identify the significant problems experienced with LWR piping systems along with their primary causes (1). The following paragraph summarizes the findings of this survey.

Pipe cracking was identified as the most recurring problem. The most significant cause of pipe cracking was determined to be piping vibration. Problems with pipes and pipe fittings were found to be responsible for approximately 10% of all safety-related events and 7% of all outage time at LWR's. Mechanical vibration was the cause of 22.3% of all reportable occurrences involving pipes and fittings. A reportable occurence is an unscheduled incident or event that the NRC determines is significant from the standpoint of public health of safety. Licensee Event Report, LER, is a generic term for reportable occurrence. Messrs. Kustu and Scholl ranked as highest priority the need for research in the area of pipe vibration.

A separate summary of LER's through October 1978, documented eighty-one pipe cracks that were directly attributable to vibration (2). All of the cracks were in pipe sizes less than four inches. More detailed review of the LER's demonstrated that cracks in tap lines were a prevalent source of failure. The frequency of small tap line failures has also been verified by personnel familiar with start-up testing and operation of LWR plants.

FAILURE CAUSES

Vibration Source

During plant operation, there is normally no flow through tap lines. Vibrations in tap lines are therefore primarily induced by the header piping to which the tap lines are attached. All piping with flow will vibrate to some extent. Vibrations in the header piping can result from pressure pulses induced by pump operation from vortex shedding; and from flow turbulence, cavitation and flashing. Mechanically induced pump vibrations and fluid pulsations are also sources of tap line vibrations.

Tap Line Characteristics

Several characteristics of tap lines make them susceptible to vibration failures. The valves and fittings typically used for these lines have masses much larger than the mass of the piping. If these lumped masses are not supported they can cause large inertial forces, which will in turn cause large moments at the nozzle connections. Additionally, lumped masses lower the natural frequency of the tap lines. Flow induced vibration is normally low frequency (<30Hz). If a tap line has a low natural frequency it is more likely to be excited in resonance with header piping vibrations. The detrimental effects of large lumped masses are exacerbated when double isolation is required. Double isolation increases the lumped masses by necessitating the use of either two valves or a double block valve. Equation (1) demonstrates the significance of resonant vibration. This equation is the steady state response of a single degree of freedom system excited in resonance (3).

$$X' = \frac{x}{2\beta} \qquad (1)$$

For example, if a tap line in resonance with header vibrations has a structural damping (β) equal to 1% of critical damping, then the header vibrations (x) will be amplified in the tap line (X'= tap line vibrations) by a factor of 50.

Steady state vibrations quickly build up a large number of stress cycles. A 10 cycle per second vibration results in greater than 10**8 stress cycles in a year of continuous operation. The large number of stress cycles that result from steady state vibration means the vibratory stresses must be kept below high cycle fatigue stress limits. If the vibratory stresses in the tap line exceed the endurance stress limit for the material (=10ksi(70MPa) for carbon steel (4)) then a fatigue failure will occur.

Another contributing factor in tap line failures is the lack of attention these lines receive in their design and installation. Tap lines are commonly field routed and supported. Ease of installation if often the governing criteria. Mitigation of vibration effects has been rarely considered in the past. The large number of failures in these lines is a consequence of the lack of emphasis given to tap line design and installation.

AVOIDING FAILURES

Design Requirements

Vibration induced failures of tap lines can be readily avoided. Since vibration is the primary cause of failure for these lines, the basis for their structural design should principally be the mitigation of vibration effects. This will preclude the usual practice of uncontrolled field routing tap lines.

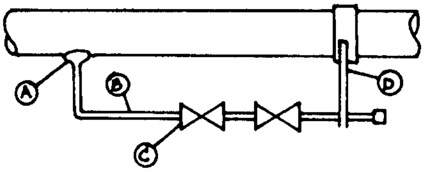
To develop effective vibration resistant designs, the routing and support must be considered in conjunction. The following requirements, as illustrated in Figure 2, should be adhered to when designing tap lines.

A) Reinforced branch connections should be used. Vibration failures usually take the from of a crack in the weld between the branch and nozzle or between the nozzle and tap piping. Reinforced connections are available that will better distribute the stresses in the header and tap line piping.

B) The span of piping between the header and first support should be kept as short as possible. A short span will have a high natural frequency, which will help to avoid resonance with header vibrations.

C) Large lumped masses, e. g. valves and fittings, must be rigidly supported. This is the most important aspect of the design. Unsupported lumped masses are the major contributor to vibration failures. The unsupported masses both lower the span's frequency and can cause large inertial forces.

D) Routing the tap line parallel to the process piping allows it to be supported from the header. This enables pipe span between the nozzle and support to be kept short which gives it a high natural frequency. This routing and support configuration also avoids relative motion between the header and tap line, i.e. the header and tap move as a rigid body.



A. Reinforced Branch Connection
B. Pipe Span Length Tuned to Avoid Resonance with Header Vibrations
C. Lumped Masses Rigidly Supported.
D. Small Line Supported From Header, Avoids Movement Of Small Line Relative to Header.

FIG. 2 Tap Line Routing And Support Requirements

Standard Configurations

The above design practices are best implemented by the development of generic or standard tap line routing and support configurations. Several standard configurations will likely be necessary to adequately address all of the various types of tap lines found in a LWR plant. Figure 3 presents two examples of standard configurations. These designs have been used for pressure taps, vents and drains requiring double isolation. These examples support the tap lines from the header piping. Finding room to add a support on the header piping is often difficult ; therefore, having more than one design is necessary to allow installation in a wide variety of applications. Providing tolerances on the specified dimensions will also help to insure the feasibility of installing the standard configurations.

Standard configurations can be developed to cover most applications ; however, a few situations tend to defy their use. A notable exception are tap lines originating from process piping valves. As Figure 1 illustrates, there are often several different tap lines associated with these vales. Design requirements A through D above are still supported from the process valve or piping. The tap lines should be supported from the process valve or piping. The best way to handle this is to require the process valve manufacturers to provide tap line supports inherent to the valve.

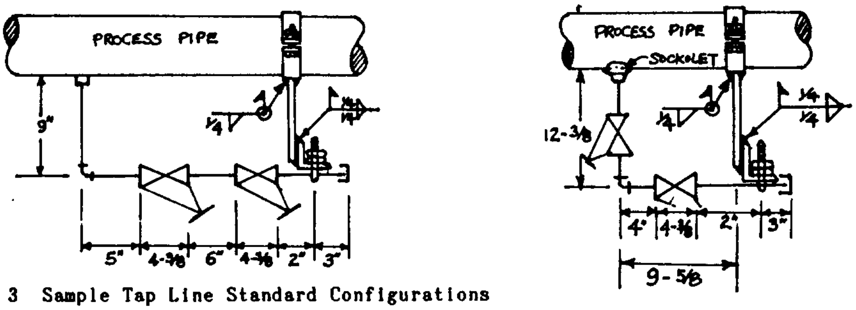


FIG. 3 Sample Tap Line Standard Configurations

Benefits

Benefits derived from the use of standard configurations and the concomitant and the concomitant support and routing requirements are realized in the areas of analysis, installation, plant testing, and most importantly, plant reliability and safety.

Through the use of standard configurations the analytical effort required to qualify tap lines is considerably reduced. The analysis performed to qualify the standard configurations are applicable to all installations where the configurations are used. Without the use of standardized designs there can potentially be hundred of different tap line routing and support installations. The analytical effort needed to qualify all the difference installations would increase accordingly.

Installing the tap lines can be done more efficiently when standard configurations are used. Experience gained installing the same type of designs will increase efficiency. Time is saved by eliminating the need for determining unique routings and supports for each installation. Extraneous supports and their associated auxiliary steel can also be avoided through the use of standard configurations. A comparison between designs used at two different boiling water reactor (BWR) plants exemplifies the potential benefits that can be gained. Each of the BWR plants has four main steam headers inside their containment buildings. Each of the headers has a flow venturi with four pressure tap lines. These lines have were condensing chambers which must be supported. In one plant the 16 different tap lines uniquely routed and supported. This required 14 rigid supports, 22 snubbers and 8 spring hangers to support the condensing chambers alone. All of these supports and associated auxiliary steel were avoided in the other plant by supporting the condensing chambers from the main steam headers. Both plants adequately supported these tap lines : obviously, however considerably less effort was needed in the latter case.

The governing power piping codes, ASME Boiler and Pressure Vessel Code - Section III and power Piping ANSI B31.1, along with various U.S Nuclear Regulatory Commission Regulatory Guides (e.g. 1.68 & 1.70) require that piping vibration be addressed during the plant testing stage (5). If vibration mitigating designs are used for tap lines, then less consideration need be paid these lines during plant testing. Waiting until the testing stage to address tap line vibrations will require a substantially greater testing effort and will likely result in backbit work.

Vibration related failures of tap lines detrimentally affect plant reliability. A crack in a tap line may necessitate an unscheduled outage. Cracks can result in leakage of contaminated fluids, which will hamper plant maintenance. Additional paper work may also be necessary to document failures. Avoiding tap line failures has the significant benefits of enhancing plant reliability and safety.

Design & Analysis Details

The balance of this paper delineates design, analysis and implementation techniques that are used to develop plant specific standard configurations for tap lines.

DESIGN CONSIDERATIONS

Tap lines should be designed primarily to minimize the effects of steady state vibrations. The objective is to obtain a design that will both withstand all of the operating and postulated accident loadings and also mitigate vibrational effects. A vibration resistant design should easily satisfy other dynamic design-basis loadings.

Generally, prediction of the exact magnitudes and wave shapes of steady state piping vibrations is not practical. Therefore, good layout and design practical, rather than analysis, are the most effective means of controlling vibrations. The routing and supports should be considered together in the development of tap ling designs. For example, a good routing layout does little good if the support has not been designed with vibration in mind.

Routing

The objectives of the routing are to avoid resonance with header vibrations and to allow the lumped masses to be rigidly supported. Other considerations include any applicable drainage and slope requirements; installation feasibility; and ease of maintenance and operation. The routings should also avoid interference with the insulation. If the piping insulation is not considered in the routing design, then the insulation may have to be coped out. This is especially true for tap lines on process valves (Fig.1) and when mirrored insulation drawings should be checked to avoid interferences. Coping out insulation is not only more work but it results in greater heat losses and decreases plant efficiency.

Another consideration is the minimum distance between welds. This distance is required to prevent interaction of peak stresses. The distance between welds must be greater than the valve indicated by the following formula (6):

$$d_{min} = 2.5\sqrt{rt}$$

where d = minimum distance between welds
r = pipe mean radius
t = pipe mean wall thickness

For a tap line comprised of sch.80, 3/4" pipe size, this value equals 0.71" (18mm). Note that for small diameter piping this minimum distance should be increased to facilitate installation, i.e. a minimum of 2.5" (64mm) should be allowed between fittings to allow room for welding.

Tap Line Routed Parallel To Header. Routing tap lines parallel to the header results in the best design configuration. This allows for a very rigid design configuration. This allows for a very rigid design and has the benefit of minimizing the required supports.

During operation there is usually no flow in tap lines. Because of this the heat from the header process fluid rapidly decays. The tap line will therefore be at a lower teperature than the header. Referring to Figure 4, the header expansion Δ, will be greater than the tap line expansion δ. This differential expansion must be designed for. Flexibility must be included in either the support or the routing to absorb the differential expansion.

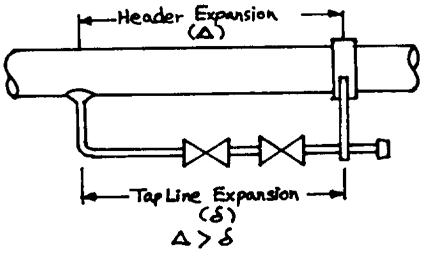


FIG. 4 Differential Thermal Expansion

Cantilevered Tap Lines. This routing is acceptable only for very short tap lines with relatively small lumped masses. Figure 5 is an example of a cantilevered design; this arrangement has only relatively small valve. For this type of line the cantilevered branch will be rigid and have a high natural frequency. Therefore, resonance with header vibrations can be avoided and the branch and header should move together as a rigid body. Note that inertial forces may generate large moments with type of design.

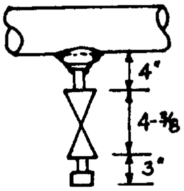


FIG. 5 Sample Cantilevered Tap Line

Valves Supported Indepenent of Header. There are circumstances where it is not feasible to support the tap line from the header. In these cases the tap line valves are supported independently of the header. The spapipe between the header and first set of rigid supports on the branch line is routed with sufficient flexibility to absorb movements of the header piping.

Tap line valve masses are large in comparison to the mass of the piping and unsupported lumped masses have the most detrimental effect on the ability of the branch line to withstand vibratory loadings. Therefore, rigidly supporting the valves is the primary consideration in the routing of these small branch lines. When the tap line is supported independent of the header the valves are located near and rigidly supported from structural steel in the vicinity of the branch connection.

Support
The stiffness characteristic of the support is a key design criterion. The support may be required to absorb displacements and would therefore have to be designed flexible enough to prevent overstress of the tap line piping. Supports can be designed to be flexible yet still be sufficiently rigid to control vibrations.

<u>Support From Header</u>. Figure 3 illustrates one type of support from the tap line header piping. The principle element of this support is made from a 3" * 3/8" (76.2 * 9.53mm) plate. A plate is used because it has a relatively large moment of inertia about the flexible plane of the branch (plane formed by branch spans perpendicular and parallel to the header), and a small moment of inertia in the direction of the differential expansion between the tap and header piping. The plate design allows the support to adequately support the tap line for vibration and still be flexible enough to absorb the expansion movements. The angle is used in the design to provide adjustment. The angle is butted against the tap piping and plate and is then welded in-situ. This ensures a tight fit between the branch and angle. AU-bolt be tightened to eliminate gaps.

Figure 6 illustrates two examples of stiff support designs. These designs have larger loading capacities. They are used for low temperature applications or when sufficient flexibility has been designed into the tap line routing. Both designs use two U-bolt offer better moment restraint. The single U-bolt design relied on friction to restrain moments. Adjustability is provided in these designs. The upper support in Figure 6 is comprised of one pipe that fits inside another. The weld between the two pipes is made in-situ to allow for adjustment. The weld between the two pipes is made in-situ to allow for adjustment. The lower design accommodates two tap lines (for the case shown pressure tap lines with condensing chambers). The welds between the plate and angles are made last to provide for adjustment. The holes in the angles can be drilled in-situ to provide for additional adjustability.

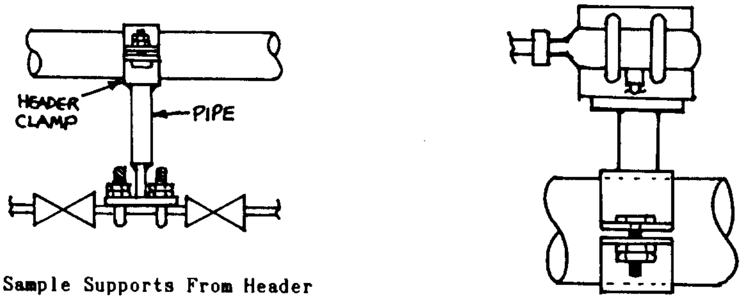


FIG. 6 Sample Supports From Header

<u>Header Attachment</u>. The designs depicted in Figutes 3 and 6 use standard pipe clamps to tie the supports into the header piping. The use of clamps avoids into the header piping. Avoiding header welds is especially desirable for backfit work where system hydro's could be affected by welding. If the supports are welded to the header they must be treated as a welded attachment in the header piping stress.

<u>One That Failed</u>

Figure 7 is a photograph of a tap line that has experienced several failures. A crack developed in the weld between the header coupling and tap line piping. When the crack first appeared the tap line was built up and the support shown in the failure the weld was built up and the support shown in the photo was added. After these modifications were made the tap line again failed. Both failures occurred after a short period of time during flushing of the system.

This tap line is made up of sch.80 1 1/2" pipe size carbon steel pipe and a double block valve weighing 40 lbs.(178N). The distance from the header to the valve is 8" (203mm). The valve is welded directly into the elbow.

The routing of this tap line is short; however the large unsupported lumped mass obviously had detrimental effects. The first failure of this line emphasizes the need to support large masses.

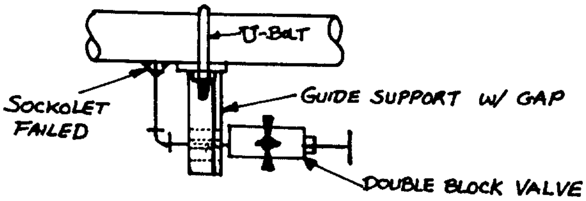


FIG. 7 Failed Tap Line

The second failure of the line emphasizes the need to develop appropriate support designs. Figure 8 details the support used in this design. The most conspicuous error in this design is the specification of 1/16" (1.59mm) gaps. (Gaps are typically specified for Piping supports to allow thermal movement of the piping). Piping vibrational displacements equal to 1/16" (1.59mm) at the support location are much larger than the magnitude needed to fail the piping. Therefore, the gaps rendered the support useless.

Even if no gaps had been specified, the effectiveness of this design would be questionable. The support was located very close to the elbow. This is a very rigid region of the routing and to be effective, a stiff support is needed. As can be seen from Figure 8, the lateral stiffness of the support results from the friction between the plate and pipe saddle, and from the bending stiffness of the U-bolt around the header. Therefore, the lateral rigidity of the support depends almost entirely on the frictional resistance between the plate and pipe saddle. Unless the frictional forces are large the support would not be effective, even without gaps.

This support has been replaced with one designed according to the requirements discussed above. No failures have since been experienced.

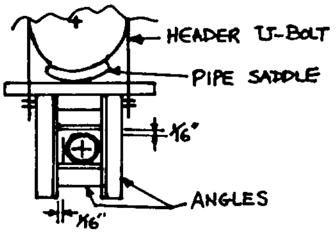


FIG. 8 Poorly Designed Support

ANALYTICAL CONSIDERATIONS

Tap line designs are analyzed for all the normal operating and postulating accident loadings and postulating accident loadings and can be qualified via standard piping analysis methodology. However, there are a few considerations unique to tap lines and these are discussed below.

Stress Qualification

Piping. The objective of tap line design is to keep the peak vibratory stress below the fatigue endurance limit for the piping material. Yet, attempting to predict the actual vibratory loadings that a particular tap line might experience, is not recommended. Steady state vibrations depend on a large number of variables. Accurate analytical prediction is generally illusive and expensive. Heuristic approaches may be used to adequately consider the effects of vibration. For example, conservatism can be added to other design loadings to implicitly consider vibration. Alternatively a hypothesized time history ca be used.

Peak stress indices should be used when evaluating vibratory stresses, as fatigue is the primary consideration. The product of the moment loding secondary and local stress indices, C and K , respectively from the ASME Code (7) is the appropriate peak stress index for piping components. Two times the ASME Code (8) intensification factor (2i) may also be used for the peak stress index.

Support. Several unique considerations must be addressed in the support qualification. If a clamp is used to tie the support into the header, then the clamp must be qualified. The manufacturer's allowable loadings are no longer applicable because the clamp is loaded in a non-standard manner, From experience, for the majority of applications, standard clamps have been proven acceptable for header pipe sizes 10" and above and heav clamps are needed for pipe sizes below 10". Note that when a tap line is supported from the header piping, the mass of the tap line and its support may have to be considered in the header analysis. Usually this added mass is negligible.

When the supports are welded directly to the header, the welded attachment effects (e.g. Reference 9) must be considered in the header analysis. If U-bolts are used in the design, they may be subjected to large side-loadings. This is especially true when two U-bolts are used for restraining moments. The couple loadings in the U-bolts may exceed the side-loading capacities specified by the manufacturers. Experience has shown the actual side-loading capacities to be larger than those specified by the manufacturer. Calculations or testing can be performed to obtain realistic U-bolt side-loading capacities.

Static Loadings

Thermal Expansion. As mentioned earlier, the heat from the process fluid is transferred only a short distance into the tap line piping. The tap line temperature is therefore lower than that of the process piping. This becomes significant when the tap line is supported from the header. The differential expansion between the header and tap piping must be taken into account.

Figure 8 delineates the axial temperature distribution in a tap line.
This distribution is conservative in that it represents a lower bound of the temperatures. The following assumptions were made in generating these curves.

1) A finite element computer program (10) was used to solve the one dimensional steady state heat conduction problem.
2) A free convection boundary condition was used.
3) Pipe Conductivity, Kp = 26.1 Btu/Ft-Hr-°F (45.1W/m.K)
4) Insulation Conductivity, Ki = 0.042 Btu/Ft-Hr-°F (0.073W/m.K)
5) Film Coefficient Convection and Radiation, h = 2 Btu/Ft -Hr-°F (11.35W/m .K)
6) Insulation thickness equals 2 inches.
7) Fluid inside tap line piping is assumed stationary.
8) Conduction of pipe contents is assumed negligible.

Bolt Torques and Friction. Friction is relied on to provide much of the restraining force when a header clamp is used to support the tap line from the process piping. Ample frictional resistance can be obtained by torquing the clamp bolts.
As Table 2 demonstrates, relatively small torque loadings are required to obtain the needed frictional resistance. The following equations were used to calculate the tabulated values.

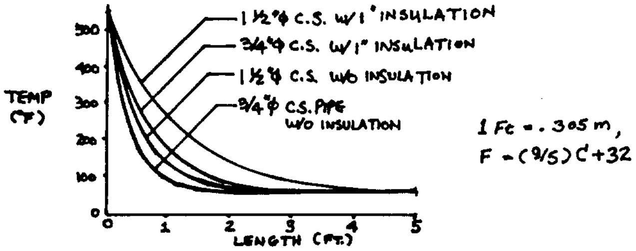


FIG. 9 Axial Temperature distrubution in a Tap Line

Obtained by torquing the clamp bolts. As Table 2 demonstrates, relatively small torque loadings are required to obtain the needed frictional resistance. The following equations were used to calculate the tabulated Values.

Clamp Load (11) $P = T/(k.Dn)$ (3)
(per bolt)

Axial Fritional Resistance $F = f.4P$ (4)
(axial direction of header)

Torsional Frictional Resistance $TR = 2P_x Doxf$ (5)
(torsion about header axial direction)

where: $k = 0.2$ (assumes dry fasteners)
$f = 0.23$

TABLE 2

HEADER CLAMP FRICTIONAL RESISTANCE

Do Inches	Dn Inches	Axial Resistance (lbs)		Torsional Resistance (ft-lbs)	
		T = 10 ft-lb	T = 30 ft-lb	T = 10 ft-lb	T = 30 ft-lb
4.5	5/8	884	2652	166	497
6.625	3/4	736	2208	203	610
10.75	7/8	632	1896	283	849
20	1 1/8	490	1470	409	1227

1 lb = 4.448N

1 ft-lb = 1.356 N.m

1 inch = 25.4mm

Dynamic Loadings

A tap line routing and support configuration that is designed to mitigate effects of steady state vibration should have little trouble satisfying other design basis dynamic loadings (e.g. postulated earthquake loadings). Standard configurations can be qualified for any location and orientation in the plant. If response spectra in the plant. If response spectra analysis is used then enveloping spectra at all locations in the plant along with enveloping spectra in the three orthogonal planed will produce design spectra that can be used to qualify the configurations for installation anywhere in the plant. This approarch has proven acceptable for standard configurations such as those shown in Figure 3.

Design Comparison. The results of tap line dynamic analyses are useful for evaluating different designs. If response spectra analysis is used, then the calculated frequencies and participation factors are helpful evaluation criteria. Designs with high natural frequencies will avoid resonance with high natural frequencies will avoid resonance with header vibrations and small participation factors will minimize the virational response. It's interesting to note that for the upper design shown in Figure 3, the first mode frequency increases approximately 50% and the frist mode participation factors decrease approximately 50% when the center of gravities of the valves are rotated 180 out of phase.

Uniform base excitaion response spectra and multiple support excitation time history techniques were used to analyze the routing configuration shown in Figure 7. This tap line was modeled without a support (cantilevered) and with a support attached to the valve from the header. Spectra equal to 1.0g at all frequencies were used for the response spectra analyses; sinusoidal base excitations equal to 1.0g and with frequencies equal to the frist frequency of each model were used for the time history analyses. The intent of the time history analyses was to simulate the tap line vibrating in resonance with the header vibrations.

When a support was added, the first mode frequency increased to 147Hz from 39Hz and the participation factors decreased 20%. Adding a support to the valve reduced the stresses by a factor of 3.5 for the response spectra analyses and reduced the stress by a factor of 6.4 for the resonant time history analyses. This dramatic improvement in the tap line's dynamic characteristics and stresses, resulting from the addition of a support, emphasize the importance of supporting large masses.

IMPLEMENTATION

Successful implementation of the routing and support techniques outlined above involves paying careful attention to the installation of the tap lines. The lines should be installed to closer tolerances than the balance of piping. The as-built configurations should be inspected to ensure that there are no gaps in the support.

If the support has been designed with specific flexibility characteristics, then measures need be taken to assure that different size structural members are not substituted into the design. If the lines are to be supported from the header then room for the support may have to be reserved on the process piping.

For plants in advanced stages of construction, may of the tap lines already have been installed. The use of these routing and support techniques if still recommended.
This will obviously result in some backfit work, however, the benefits resulting from the use of the prescribed techniques should make this work well worthwhile.
When the cost of replacement power can exceed 5500,000 per day, just preventing one say of outage time through the use of these techniques, can justify the requisite backfit work. Savings in the number of required supports and a reduction in the analysis effort will also result.

CONCLUSION

Piping vibration has been identified as the most significant cause of pipe cracking.
A predominant number of these vibration related failures have occurred in small tap lines. Tap line vibration failures can be avoided through the use of routing and support techniques that are designed to mitigate the effects of steady state vibration. These techinques can be used to develop standard configuration which have the additional benefits of minimizing the efforts required for analysis, testing and installation. Implementing a program that results in vibration resistant designs is recommended for all plants. The efforts expended will be justified by the benefits derived from a successful program.

NOMENCLATURE

Btu	British thermal unit
Dn	nominal bolt diameter, inches,for pipe clamp
f	friction coefficient
F	degree in fahrenheit
Ft	feet
g	acceleration of gravity
h	film coefficient: Btu/FT-HR- F
HR	hour
Hz	hertz, cycles per second
k	torque coefficient
K	thermal conductivity: Btu/FT-HR- F
lb	pound
psi	pound per square inches
p	clamp load
T	installation torque: ft-lbs
WT	weight: lbs
D	pipe outside diameter

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