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Forensic Engineering Investigation of Failure of an Oil Pipeline

by William R. Broz, P.E. (NAFE 352C)

Abstract

A below-grade, NPS 12 pipeline serving a major commercial marine terminal failed at a flanged joint, causing a major leak and contamination of the surrounding soil. The gasket at the failed joint showed evidence of localized, radial through-leakage. At the terminal, the initial excavation of contaminated soil caused minor damage to several non-leaking segments of pipe and the author was first tasked to oversee the related inspection, weld repair and corrosion protection work. The author subsequently performed a forensic pipe stress analysis of the affected portion of the fuel oil system per the governing pressure piping code. The results indicated that the leaking joint failed with respect to the code criterion of *equivalent pressure*. Further investigation revealed that the system as originally designed was entirely of butt weld construction with no flanged joints, and would have complied with all code requirements. The investigation determined that the general contractor had made an unauthorized substitution of flanged joints for butt weld joints, without informing the owner or design engineer of record.

Keywords

Pipe; piping system; fuel oil; expansion joint; ASME Boiler and Pressure Vessel Code; ASME Code for Pressure Piping B31.3 (Process Piping); code allowable stress; pipe stress analysis; equivalent pressure

Background

In July 1999 the author received a request for assistance from contract engineering staff at the Port of Seattle (POS). A major oil spill had occurred at the Terminal 91 complex (consisting of Piers 90 and 91 and contiguous uplands), resulting in extensive contamination of soil at Pier 90. Excavation and remediation operations were underway, and the author was retained to oversee the repairs and corrosion prevention measures for approximately 750 lineal feet of piping exposed during excavation.

Upon arrival at the site, POS staff met with the author and provided background on the spill. The source of the leak had been identified: a flanged joint in a nominal pipe size (NPS) 12 subgrade fuel oil line, located in a concrete vault on the Pier 90 site (Fig. 1). The gasket had been recovered from the failed joint and exhibited clear evidence of flow erosion through its radius, suggesting that gasket decompression had occurred. No distress was noted in the flange faces, bolts or nuts.

William R. Broz, P.E., 1411 7th Street #201, Santa Monica, California 90401

Incident Site

The POS is the largest marine terminal complex in the Pacific Northwest (Ref. 1). Combined with the Port of Tacoma (of approximately equal size but under separate governance), the two ports taken together comprise the second-largest seaport on the U. S. West Coast. The POS's Terminal 91 facility (Fig. 2) is located in the northwest portion of Seattle's Elliott Bay (part of Puget Sound), between Magnolia Bluff and Queen Anne Hill and directly south of the Magnolia Viaduct which connects the two neighborhoods. The facility is a breakbulk operation; at the time of the incident it handled primarily fuel oil, grain and frozen foods as well as automobiles. It is physically separated from the larger container complex situated in the Duwamish Waterway to the south (not shown).

Figure 1
Concrete vault following incident, depicting fuel oil lines and flanged-end ball expansion joints

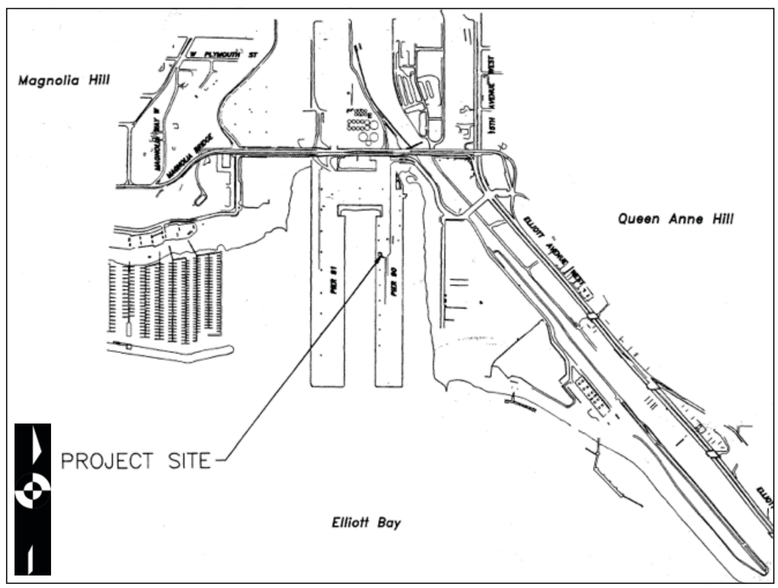

Figure 2
Port of Seattle Terminal 91 Complex

Directly north of the Magnolia Viaduct was a petroleum oils and liquids facility that had served Terminal 91 for several decades prior to the subject incident (Fig. 3). The operator of the facility at the time of the incident was the Pacific Northern Oil Company (PANOCO). In 1995 three subgrade fuel lines (NPS 6, 10 and 12) were installed between the PANOCO facility and a retail fuel dispensing facility at the foot of Pier 90. The lines provided several grades of fuel oil ranging from No. 6 to marine diesel (No. 2, low-sulfur).

Key Engineering Terms

The following terms are used in the balance of this paper.

Code allowable stress refers to a set of maximum stresses specified in the governing piping design standard for a particular jurisdiction or facility. For POS, the governing standard was ASME B31.3, *Process Piping* (Ref. 2), one of the "book sections" from the ASME B31 series, *Code for Pressure Piping*. The 1998 edition of ASME B31.3 was in effect at the time of the incident (the code was re-

Figure 3
Aerial photo of Pier 91 complex, looking west.
Pier 90 is at lower left; the PANOCO tank farm complex is to the right of the Magnolia Viaduct.

vised on a three-year cycle at that time). Allowable stresses are defined and tabulated in ASME B31.3 for approved materials, typically at one-third the ultimate tensile strength. Allowable stresses are temperature-dependent.

Primary or **sustained stresses** result from the requirements of static equilibrium (Ref. 3). Dead load (weight), live load (e.g., wind and snow) and seismic loads are examples of external forces resulting in primary stresses. They are typically not self-limiting, and catastrophic failure can result from a single application. The failure mechanism is plastic deformation through most of the affected pipe or component.

Secondary or **displacement stresses** are those resulting from imposition of a defined strain field, independent of static equilibrium (Ref. 3). Examples include cyclic stresses such as thermal or vibration. Secondary stresses are typically self-limiting, and are accommodated through local yield or minor distortions. A well-known example is a pipe heated into the creep regime: the thermal stress “relaxes” as plastic deformation occurs. Fatigue is the typical failure mechanism. Secondary stresses are usually considered independently of primary stresses, as the failure mechanisms are different. Empirical evidence suggests that, under some circumstances, primary and secondary stresses reinforce one another (Ref. 2). Piping codes in common use today reflect this phenomenon.

The **stress intensification factor (SIF)** is a local increase in stress due to concentration of the strain field at a geometric discontinuity. A classic paper by Markl in 1952 (Ref. 4) laid the mathematical foundations of the SIF. The SIF is inversely proportional to the “flexibility” of a component, the latter having a specific mathematical definition per Markl, but also conforming to the commonly-held qualitative understanding of a flexible system as one capable of absorbing strain without plastic deformation.

An **expansion joint** is an engineered device that accommodates piping system displacement in a defined direction and magnitude – that is, creates flexibility. Manufacturers offer a very broad variety of types and configurations; common ones are bellows, ball and slip. The expansion joints installed at Pier 90 were of the ball type, essentially ball-and-socket joints (Fig. 4). Joints develop systemic forces due to internal pressure and the frictional force required to initiate joint displacement, depending on type.

Nominal Pipe Size (NPS) is the most commonly used designator for pipe in the U.S. It corresponds roughly to the outside diameter of the pipe in inches. Together with **pipe schedule,** which correlates with wall thickness, it specifies the dimensional requirements of pipe for design and procurement.

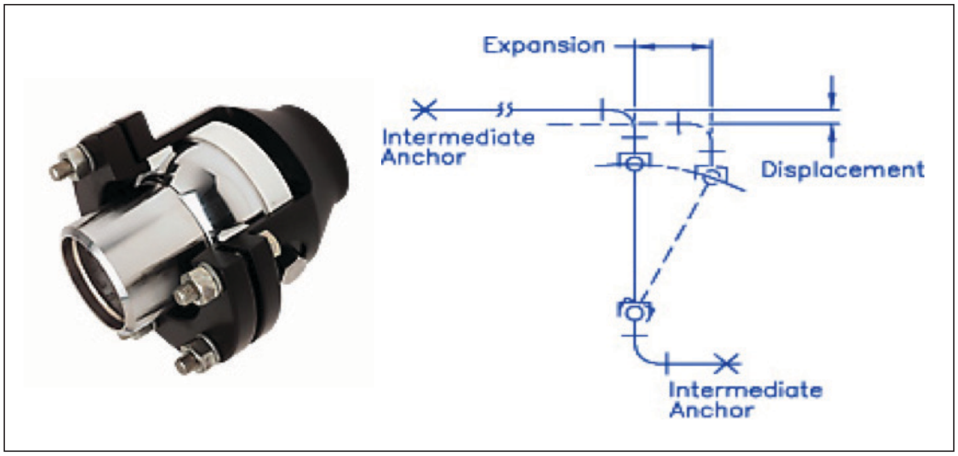

Figure 4
Typical ball-type expansion joint (left); typical installation and design displacement (right)

Pressure class for pipe flanges in the U. S. correlates roughly to the design pressure of the associated piping system in pounds per square inch gauge (psig). Common pressure classes for carbon steel flanges are Class 150, 300, 400, 600, 900, 1500 and 2500, with flanges generally becoming thicker and wider, and having more/larger bolt holes, as the class increases. The actual design pressure of a flanged joint depends on its operating temperature as tabulated in the governing dimensional standard (Ref. 5). The design pressure becomes equal to the nominal pressure class at a temperature somewhat above ambient; as a consequence, the design pressure at lower temperatures is actually higher than the nominal pressure class would suggest.

A **pipe anchor** is a type of pipe support which, for the purposes of stress analysis, is considered to completely restrain a pipe in all six degrees of freedom (3 displacement axes and three corresponding moments).

Facts Known

The following information was initially known by POS staff and subsequently confirmed by the author through site inspections and review of contract documents:

- Piping was ASTM A53 Grade B Schedule 80 carbon steel pipe, direct buried and protected from corrosion by a zinc-rich primer and single overlapping layer of polymer pipe tape
- All three fuel oil lines included a 30-degree offset (dogleg) on Pier 90 (Fig. 5). On the offsets, pairs of ball-type, flanged-end expansion joints absorbed thermal expansion from temperature variation in the product. The offset piping and expansion joints were located in a buried concrete vault with manhole access.
- The leak location was a flanged joint connecting an expansion joint to an adjacent segment of NPS 12 piping on the 30-degree offset.

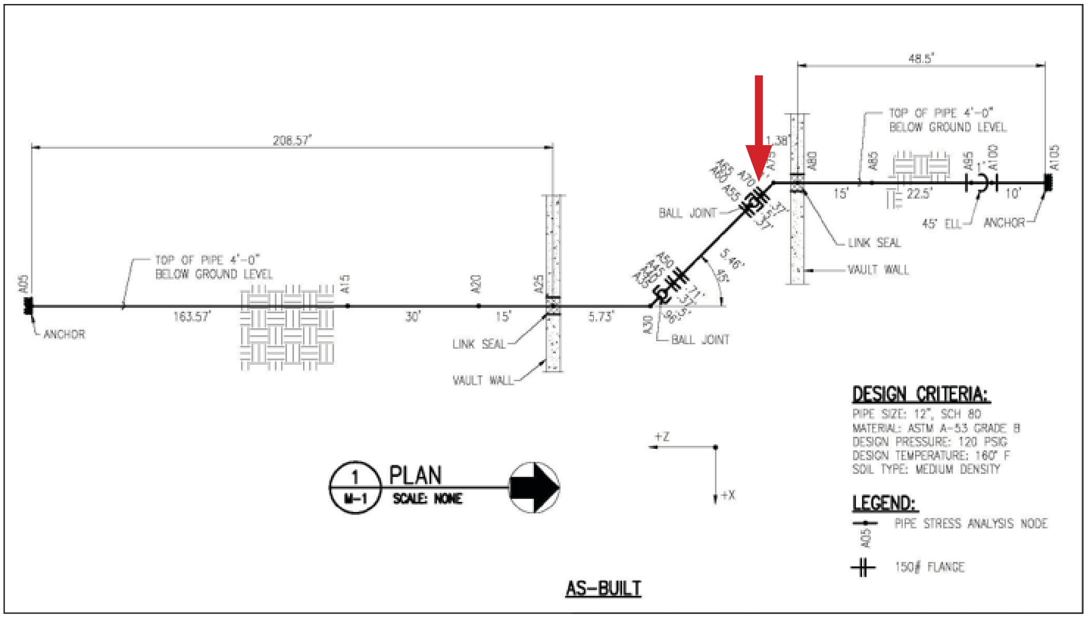

Figure 5

As-built configuration of NPS 12 piping system surrounding the incident site, showing piping offset and expansion joints in the concrete vault. The arrow indicates the failure location.

- Flanges at the expansion joints:
  - ASTM A105 forged steel, Class 150, raised face, dimensions conforming to ASME B16.5
  - High strength steel bolts and heavy hex nuts conformed to ASTM A193 and A194 respectively
  - Synthetic elastomeric gaskets with good chemical resistance to petroleum products
- Design temperature was 160° F.; design pressure was 120 psig
- Product carried by the failed NPS 12 line was marine diesel
- First visual indication of the incident was oil flowing from the closed manhole cover on the concrete vault
- Oil inundated the surrounding soil, but none entered Elliot Bay
- Fuel oil piping had been in service approximately four years at time of incident.
- The failed gasket displayed clear indications of through-erosion in the radial direction.

Immediate Action

POS initiated its oil spill protocol immediately upon discovery of the leak, including isolation and de-pressurization of the affected and adjacent fuel lines. Standing oil was recovered from the concrete vault, and excavation then commenced to determine the extent of soil contamination. Inundated soil (Fig. 6) was excavated and hauled to an approved offsite disposal facility. In the process, approximately 260 lineal feet of each of the three subgrade lines were exposed.

The extensive excavation disrupted normal operations at Pier 90, and for this reason there was a strong business imperative to re-bury unaffected segments of piping and return the pier to its pre-existing condition. The excavation operations, however, had caused surface damage to some of the piping. Where the existing pipe tape had been scored from the excavation, it had been removed to expose the bare piping.

Figure 6
Typical example of contaminated soil. The concrete vault, where the oil leak originated, is in the background.

We were retained to:

- Conduct a complete visual inspection of exposed piping, noting all surface damage
- Review non-destructive examination procedures from the independent testing lab retained to assess possible damage to the pipe, not evident from a visual inspection
- Develop a protocol for assessing discontinuities in the pipe outer wall
- Develop repair procedures for damaged pipe, and for corrosion protection of pipe prior to backfill
- Perform initial inspection of the exposed pipe, as well as followup inspection of repairs in progress

Our initial visual inspection revealed damage from excavation, but apparently no significant diminution of pipe wall thickness. Nonetheless, the observed discontinuities were a source of concern. Approximately one month prior to the incident an NPS 16, high pressure natural gas transmission pipeline near Bellingham, WA failed and exploded, resulting in three fatalities (Ref. 6). Although the investigation into that incident was just beginning, the author's discussion with officials from the Washington State Office of Pipeline Safety revealed that one failure mechanism under strong consideration related to damage to the pipeline's outer wall during a previous excavation operation. The state hypothesized that a backhoe strike had gouged the outer wall of the pipe, resulting in a discontinuity and corresponding stress intensification factor (Ref. 7). This would have been an instance of secondary stress: the pressure cycling in the line could ultimately have caused a microscopic crack at the damage site to grow and propagate through work-hardening, ultimately migrating through the pipe wall and leading to a classic "fishmouth" rupture (Fig. 7). The phenomenon of cyclical fatigue stress in pressure piping is well-known and documented in the literature (Ref. 2), and thus we felt that the mechanism described by the state was plausible. Our inspection and repair protocol was developed with this in mind.

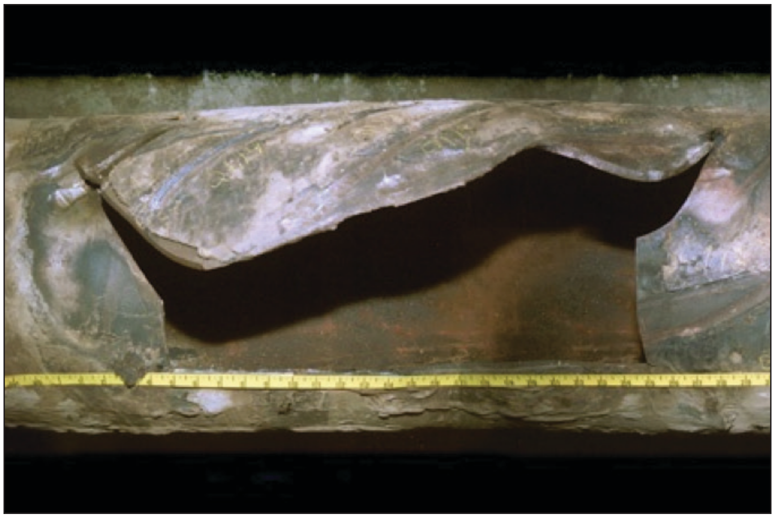

Figure 7
Rupture in Olympic Pipeline Co. high-pressure natural gas transmission pipeline

However, the specific geometry of the discontinuities observed in the field and their potential effect on fatigue stress were not well-addressed in the literature. Time being of the essence, a conservative repair approach was adopted. ASME B31.3 provided guidance for allowable discontinuity in a pipe's outer wall due to weld undercut (1/32"; approximately 1 mm) before weld repair is required. This was the criterion we ultimately adopted for the excavated lines at Pier 90. First, all gouges regardless of depth were required to be ground smooth by hand sanding, eliminating sharp radii and transitioning smoothly into the surrounding pipe wall. Dye penetrant testing was then to be performed; indications were to be sanded out and the area retested, with the process repeated until indications were eliminated. Next, irregularities in the pipe surface greater than 1/32 inch were to be weld repaired and ground flush with the surrounding pipe surface. Post-weld inspection would be random visual in accordance with ASME B31.3.

In addition to the surface discontinuity criterion, POS called for non-destructive subsurface examination of the pipe wall. The purpose of the NDE was to verify that excessive wall thinning had not occurred, and to identify possible subsurface flaws. The author reviewed and approved a random ultrasound inspection protocol consistent with ASME B31.3. Together with the surface inspection protocol and preservation methods (discussed below), the author believed this would ensure the pipe's fitness for service following re-burial.

Prior to re-burial, the author specified a corrosion protection regime consisting of the following:

- No action required for undamaged piping with intact tape wrap
- Any remaining compromised tape was to be removed, followed by inspection of exposed piping per the protocol outlined above
- For all damaged or corroded pipe, surface preparation by solvent cleaning per Society for Protective Coatings (formerly the Steel Structures Painting Council) Standard Procedure No. 1 ("SSPC SP-1"; Ref. 8) was required
- Following solvent cleaning, power tool cleaning of the same areas to bare metal per SSPC SP-11 (Ref. 9) was performed
- Field coating of damaged/corroded pipe with zinc-rich polyurethane primer

Figure 8
Typical repaired and re-wrapped piping

- Re-wrapping of all exposed pipe with 20-mil polymer pipe tape (Fig. 8). Holiday test for continuity.
- Installing contractor to submit detailed field procedures to the author for review and approval.

In addition, re-installation of the pre-existing impressed-current cathodic protection system was to be performed by others. This was coordinated by POS.

Inspection and repair of pipe proceeded methodically, as exposed segments of piping required 360-degree circumferential inspection. Procedures for bedding, backfill, compaction and pavement repair were developed by others, and the pier (less the fuel oil operation) was returned to service in May 2000.

Root Cause Investigation

POS subsequently retained this Forensic Engineer to determine the root cause of the failure, and to re-design the system. We initially recommended that a stress analysis of the three lines be conducted to determine compliance with code allowable stresses per ASME B31.3, under design operating conditions. Although the author believed that code allowable stresses were unlikely to be exceeded given the relatively low design temperature and pressure, as well as the heavy gauge of the pipe, this step was essential to a complete investigation.

Pipe Stress Analysis Background and Approach

The purpose of a pipe stress analysis is to determine the forces, moments, displacements and stresses at all points of interest in a piping system (which consists of straight pipe, fittings, and devices such as valves). *Forces and moments* are of interest to the analyst primarily due to manufacturers' limitations on equipment connections, and secondarily to obtain certain parameters needed to characterize the cyclic behavior of systems operating in the creep regime. However, there is no code-related limitation on these parameters *per se*. *Displacements* are likewise not inherently limited by code, but are critical to ensuring proper allowance for thermal growth and determining required pipe support characteristics. Stresses, by contrast, are parameters for which the code stipulates absolute limits based on temperature and material type.

In essence, the stress analysis inputs are:

- piping system material properties

- piping system physical layout
- geometry of individual valves and fittings to determine SIFs
- operating conditions (temperature and pressure; identity of pipe contents; flowrate)
- support scheme

From these are determined the resultant forces, moments, displacements and stresses. A finite element approach is common in all but the simplest systems: the analyst "grids up" the system into segments based on piping system configuration, as well as the analyst's expectations based on experience. The analysis is then a solution of a system of simultaneous linear equations, in which equilibrium conditions must be satisfied at all model node points. The relevant equations account for:

- the weight of the system and its contents (dead load)
- live loads from external sources such as wind, snow and earthquake
- material properties (e.g. section modulus, elastic modulus, coefficient of linear thermal expansion)
- support element characteristics (e.g., spring hangers; soil spring characteristics for direct-bury systems)
- operating conditions (temperature, pressure, flow)
- identity of conditions between finite element segments at the model nodes

Before widespread availability of mainframe computers, stress analysis was performed manually. This was a repetitive, tedious process involving rooms full of engineers and designers. A significant design change often resulted in a re-do of the entire computation. For about the last 25 years, reliable modeling software has been available for the PC (and for mainframes prior to that). The software, with its intuitive graphical interface and extensive material library, has made the analyst much more efficient and able to optimize solutions quickly.

The software used in our analysis was AutoPIPE, developed by Bentley Systems. It is one of a handful of PC-based applications highly regarded by analysts and prominent in the marketplace. The author had experienced years of prior, successful experience with this software.

The system model was input into AutoPIPE using the design parameters described above, and configured per the as-built field measurements (Fig. 5, above). Pipe anchors were located fairly close to the expansion joint vault on both sides, simplifying the model. One notable aspect of the model was the direct-buried nature of the piping system. In such a case the reaction of the surrounding soil must be modeled, generally by taking a finite element approach just as with the piping itself. Variables such as density, friction coefficient, and effective spring constant are determined, then "discretized" along the length of the piping much as individual pipe supports are modeled for above-grade pipe. The software itself must have provision for such an analysis, as the author's version of AutoPIPE did.

All flanges, expansion joints and fittings were modeled. In the case of the expansion joints, actual manufacturer's data were used to model the moment imposed by them on the piping system. Characteristics for commodity items such as elbows and tees were taken from the software's material library.

Results and Equivalent Pressure

The first model run for the NPS 12 line yielded an unexpected result: a flanged joint failed adjacent to one of the expansion joints – the actual failure site. The failure criterion was the engineering parameter called *equivalent pressure* (Ref. 2). Subsequent analysis of the two smaller-bore lines yielded similar results.

Equivalent pressure was a relatively new addition to ASME B31.3 at the time of the incident. Originating in the ASME Boiler and Pressure Vessel Code (Section VIII – Pressure Vessels), it ultimately migrated to the piping codes, as have other important engineering requirements in the past.

Equivalent pressure equates the effects of bending moment and axial force on a flanged joint, to that of increased pressure on an identical joint that is not subject to bending or axial force. In the analysis, it is added to the design pressure to obtain the total effective pressure acting on the joint, which is then compared to the rated pressure of the flange at the design temperature. In addition to conveniently characterizing the integrity of a flanged joint with a single engineering parameter, it accounts for the susceptibility of a flanged joint to gasket decompression due to bolt elongation under tension or bending (Fig. 9). This is not a phenomenon that affects other types of joints or straight pipe, and was not otherwise taken into account in ASME B31.3.

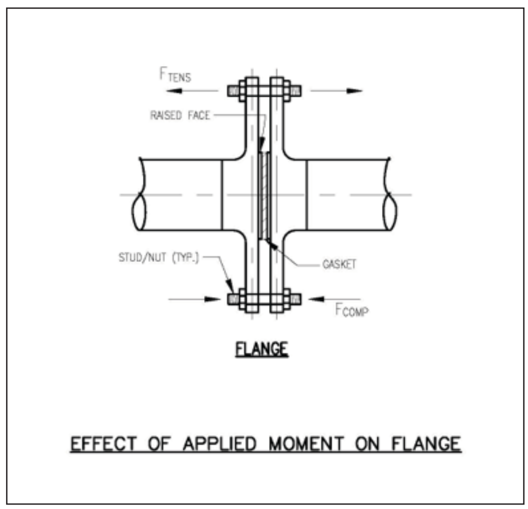

Figure 9
Effect of applied moment on flange bolt elongation

Equivalent pressure is expressed as follows:

$$P_{eq} = 16M/\pi G^3 + 4F_A/\pi G^2$$

where

P_{eq}	=	equivalent pressure, lb. per square in.
M	=	bending moment, in-lb (taken positive in all cases)
G	=	gasket diameter, in.
F_A	=	axial force, lb (taken as positive in tension)

Note that the first term on the right-hand side is of the same form as bending stress (bending moment over section modulus), while the second term is similar to axial stress (force over area). Thus the two phenomena are taken into account, and both are expressed in units of force over displacement squared (once moment is broken down to force and displacement), as is pressure (left-hand side).

Fig. 10 illustrates the effect of bending moment on the flanged joints in the offset section of piping at Pier 90. The moment originates from thermal expansion of the pipe situated between the two anchors.

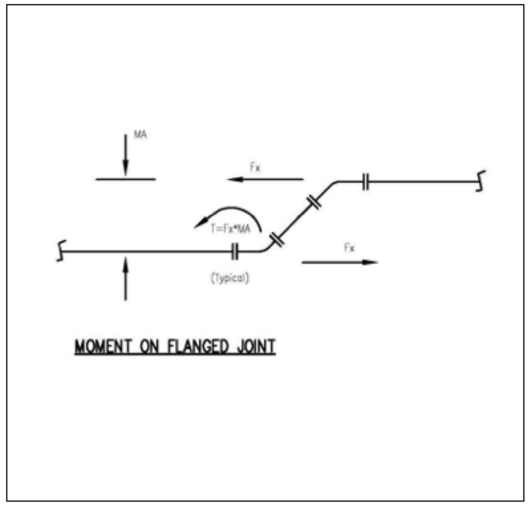

Figure 10
Schematic of moment on flanged joint due to thermal expansion

Additional Investigation

The inquiry turned next to the original design of the system, and whether a pipe stress analysis had been performed that would have uncovered the inadequacy of the flanged joints. Up to this point, the original issued-for-construction plans had not been available for review.

The issued-for-construction plans were reviewed with the engineer of record at his office. It was discovered at that time that the system had actually been designed as a 100 percent butt weld system with no flanged joints. Moreover, the engineer of record had not been retained by POS for construction phase services and hence did not review any piping submittals from the installing contractor.

Followup discussions with POS indicated they had also not received piping submittals for review. Moreover, no revised plans portraying flanged joints had been issued to the contractor after the initial issue for construction.

The piping system was analyzed for stress as originally designed by the engineer of record, i.e., as a butt-weld system. Results indicated that such a system would have fully complied with the code allowable stresses in ASME B31.3.

At this point, the author advised POS of the following:

- The system as designed by the engineer of record was compliant with ASME B31.3, and in our opinion would not have failed under operating conditions.
- The author's stress analysis for the as-installed condition indicated that the leaking NPS 12 flange was non-compliant with ASME B31.3 requirements, based on the equivalent pressure criterion.
- It appeared that the installing contractor had made an unauthorized substitution of flanged

joints for butt weld joints, without also making a substitution request or material submittal to POS, and without consulting with the engineer of record.

- The through-erosion previously observed in the failed flange gasket was consistent with loss of compression due bolt elongation under external moment.

Based on the foregoing, we concluded that the unauthorized substitution of flanged joints for butt weld joints was the root cause of the piping system failure.

It is interesting to note that the force responsible for the failure – thermal expansion – is almost universally associated with secondary stress, a cyclic phenomenon whose failure mode is typically fatigue. In this case, however, there was no evidence of fatigue or other cyclic phenomena. It would also not be accurate to characterize the flanged joint failure as due to primary stress as defined above, as there was no evidence of yield in the bolts or elsewhere in the flange. While this incident did bear some resemblance to a primary stress-related failure, in the author's opinion it is probably most appropriate to regard equivalent pressure failures in flanged joints as *sui generis*.

Followup Action

The author was retained to recommend and design upgrades to the failed portion of the system.

Much of the original system remained in satisfactory condition and the author recommended that it remain in place. This included the concrete vault (following extensive cleanup), and much of the piping. To replace the undersized, Class 150 flanges in the system, Class 300 and 400 flanges were specified as indicated by the pipe stress analysis. New expansion joints with higher-rated flanges were also specified.

The construction was completed in the summer of 2000, and the fuel oil system continued in satisfactory operation for another four years at which time the fueling operation was disestablished. Pier 90 was converted to cruise ship service, and the PANOCO tank farm was demolished.

Lessons Learned

- Believe your analytical tools and data. Our initial reaction to the pipe stress model, which indicated failure due to equivalent pressure, was disbelief based on the temperature and pressure of the system. The model's accuracy became evident, however, once the underlying physical phenomenon was considered in greater depth.
- Equivalent pressure is a useful analytical tool, and accounts for the relatively lower magnitude of bending moment and/or tensile force that would cause a flanged joint to fail, as compared to a section of straight pipe. No other method in the ASME piping codes effectively addresses this.
- It is highly advisable that project owners retain the engineer of record for construction phase services, or devote the needed expertise from internal staff. Submittal review is crucial.

- This case resolved in an especially clear and unambiguous fashion. Such a result is rare in the author's experience, but highly satisfying when it does occur.
- Our work as forensic engineers is a privilege and a trust.

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