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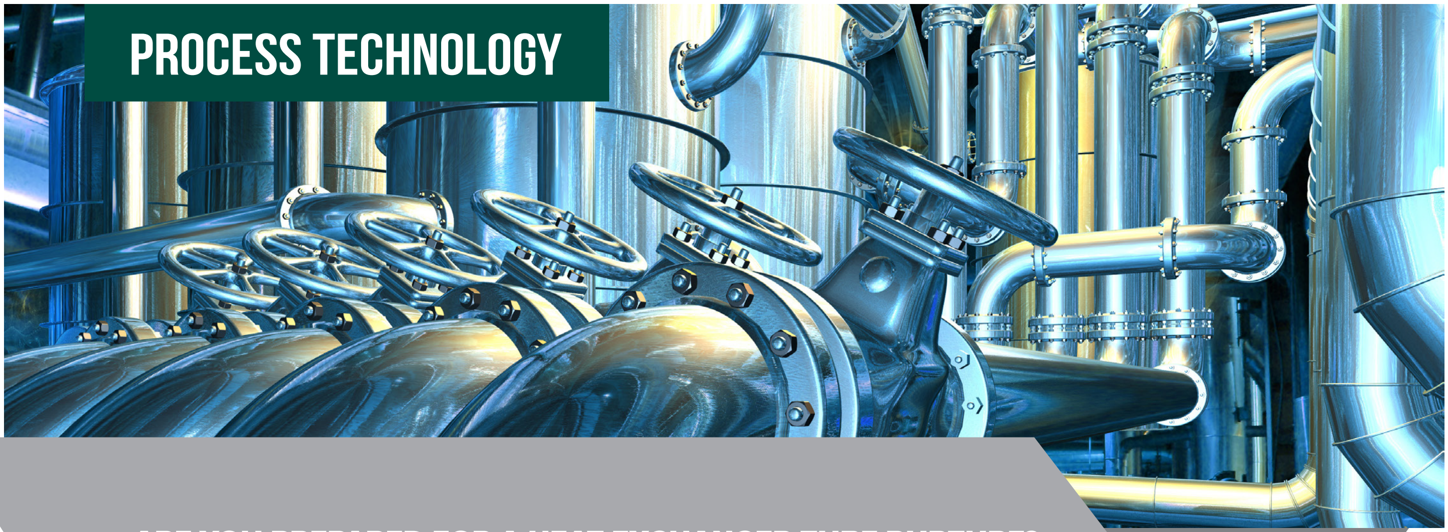

ARE YOU PREPARED FOR A HEAT EXCHANGER TUBE RUPTURE?

ANALYZING THE TUBE RUPTURE SCENARIO IN ACCORDANCE WITH API STD 521

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INTRODUCTION

When the high-pressure side of a heat exchanger is significantly higher than the pressure at which the low-pressure side was designed, damage to the low-pressure side of the exchanger or to its attached piping can occur if an instantaneous tube rupture was to occur. Instantaneous tube ruptures are extremely rare, and the decision on how to mitigate the potential risk to the low-pressure side can be difficult and confusing to the Owner/User.

API STD 521 [1], “Pressure Relieving and Depressuring Systems,” provides guidance for the heat exchanger tube rupture overpressure scenario. The standard provides two options for mitigating the risk associated with an internal tube failure. The first option is to assume that a tube rupture is going to occur at some point in time and then design the pressure relief system of the low-pressure side to handle the incoming flow. To properly design the relief system, this option may entail a steady-state solution or a much more complicated transient/water hammer analysis.

The second option is to perfom a detailed heat exchanger design analysis to prove that the probability of the tube rupture scenario is sufficiently low as to eliminate the scenario from consideration altogether. E^2G has developed a work process for analyzing both options. This article will primarily cover the second option to perform a heat exchanger design analysis, which E^2G has named a Tube Rupture Credibility Assessment (TRCA).

BACKGROUND – API STD 521 TUBE RUPTURE SCENARIO

API 521 is the industry standard (RAGAGEP) for pressure relief system design. Along with discussing other possible overpressure scenarios, the standard offers guidance regarding the design of overpressure protection of heat exchangers for the tube rupture scenario.

Although paragraph UG-133(d) of the ASME Boiler and Pressure Vessel Code section VIII, division 1 [2] requires heat exchanger overpressure protection to have sufficient capacity to avoid overpressure in the event of an internal failure, the Code has always left the determination of “credible” overpressure scenarios, as well as the definition of “internal failure,” up to the User. Designing the pressure relief protection to adequately handle a pin-hole leakage type internal failure meets the ASME Code requirement; however, extending the internal failure definition to a full-bore tube rupture scenario has always been at the discretion of the User, since it represents such a low probability event.

In past revisions of API 521, the designer was recommended to consider the tube rupture scenario only if the maximum allowable working pressure (maximum operating pressure, on a case-by-case basis) of the high-pressure side of the exchanger exceeded the hydrotest pressure of the low-pressure side of the exchanger. This became known as the “2/3rds rule,” which provided a qualitative risk assessment of what has been determined to be a relatively “non-credible” overpressure scenario. The basic philosophy was that, even though a tube rupture could result in an overpressure greater than the ASME Code-permitted accumulation of 110% of the maximum allowable working pressure (MAWP), if it did not exceed the hydrotest pressure, it would be considered a low-risk event. The "2/3rds rule" allowed the Code-maximum overpressure to be exceeded since it was a very unlikely scenario, and also recommended the tube rupture scenario be evaluated for higher risk situations where the hydrotest pressure of the low-pressure side might be exceeded.

API 521 no longer mentions the "2/3rds rule"; however, the criterion is essentially the same. The tube rupture scenario should be considered if the MAWP (maximum operating pressure, on a case-by-case basis) of the high-pressure side of the exchanger exceeds the corrected hydrotest pressure of the low-pressure side of the exchanger. This change was necessary because the ASME Code adopted higher allowable stresses for construction materials and reduced the required hydrotest pressure for these applications to 1.3 times the MAWP. Also, note that API 521 allows the User to choose a pressure other than the corrected hydrotest pressure, provided a proper detailed mechanical analysis is performed that shows a loss of containment is unlikely.

MITIGATION METHOD 1 – PROVIDE ADEQUATELY SIZED AND DESIGNED LOW-PRESSURE RELIEF CAPACITY

API 521 provides two methods to address the tube rupture scenario in applications where the low-pressure side could be exposed to pressures greater than its hydrotest pressure. The first method assumes that a full-bore overpressure scenario is remote, but credible, and requires the User to ensure that the relief protection on the low-pressure side is adequately sized and can respond quickly enough to limit the overpressure to a pressure below the hydrotest pressure.

In most applications, a steady-state solution can be used to determine the pressure relief requirements for the low-pressure system. In this case, flow is calculated across the two break orifices, and pressure relief devices (PRDs) are sized to make sure they can handle the tube rupture flow from the high-pressure side. In other applications, the design of the PRD system is much more complicated. API 521 requires a dynamic/transient pressure analysis be performed if the differential pressure between the tubeside and shellside exceeds 1000 psi and high-pressure is a gas entering into a liquid-full system (e.g., cooling water). The dynamic/transient analysis will determine the magnitude of the resulting pressure spike (water hammer). This analysis often results in the need to use rupture disks instead of conventional spring-loaded PRVs, since they will react quicker to pressure transients.

E²G utilizes our own breakthrough software, "TBREAK," to perform the transient analysis for the tube rupture scenario.

MITIGATION METHOD 2 – PERFORM DETAILED ANALYSIS ON HEAT EXCHANGER TO DESIGNATE THE TUBE RUPTURE SCENARIO AS NON-CREDIBLE

As an alternative to designing the low-pressure relief system to handle a full-bore tube rupture, API 521 allows the User to perform a detailed analysis to determine the relief system design basis for scenarios other than a full-bore tube rupture. API 521 suggests a detailed mechanical analysis of the exchanger design can be performed to show the tube rupture scenario is sufficiently remote as to be classified as non-credible. This analysis should consider, at a minimum, the following:

- Tube vibration
- Tube material
- Tube wall thickness
- Tube erosion
- Brittle fracture potential
- Fatigue or creep
- Corrosion or degradation of tubes and tubesheets
- Tube inspection program
- Tube-to-baffle chafing

Although API 521 does not cite specific methodologies for the above categories, good engineering judgement would suggest the analysis consist of, at a minimum, the following:

- A tube vibration analysis of the exchanger bundle
- A review of shell and bundle entrance velocities to assess erosion potential
- An assessment of the tube-to-tubesheet joint strength
- A metallurgical analysis to assess the likelihood for environmental stress corrosion cracking (SCC), brittle fracture, and creep
- A thermal/mechanical fatigue assessment for those exchangers that are expected to be exposed to frequent variable operating conditions
- A corrosion analysis to assess the severity of any corrosion mechanisms

- A review of the inspection programs and techniques used to determine whether they are adequate to assess the onset of cracking problems or to acquire evidence of tube pullout

E²G'S TUBE RUPTURE CREDIBILITY ASSESSMENT (TRCA) PROCEDURE

E²G has developed a TRCA procedure that aligns with the intent of API 521. E²G has constructed a flowchart that provides a decision analysis regarding whether the exchangers in question need to have overpressure protection for the tube rupture case and for determining what type of overpressure protection is required.

For exchangers in which the high-pressure side pressure exceeds the corrected hydrotest pressure of the low-pressure side of the exchanger, the decision analysis process follows one of two paths. The first path is the high-risk path, wherein the design analysis described above demonstrates that the risk of an instantaneous tube rupture is sufficiently high. In this case, Method 1 is required to mitigate the event. Recommendations are then made to design the overpressure protection system for the instantaneous tube rupture overpressure case. This design will either include actual PRDs designed to handle the full flow through a tube rupture, or will ensure that the low-pressure side piping system provides an adequate escape route to prevent the low-pressure side of the exchanger from being pressured over its MAWP. In those applications where high-pressure gas or flashing two-phase fluid can enter a low-pressure side system that is liquid-filled, the overpressure protection will also need to be able to react quickly enough with sufficient capacity to suppress the transient pressure spike that results upon tube rupture. In these instances, a dynamic simulation of the tube rupture scenario is required.

The second path through the logic diagram results when the design analysis determines that the probability of an instantaneous tube rupture is low. In this lower-risk path, Method 2 is applied, and the low-pressure side relieving system is designed for a pin-hole internal failure. The pressure relief system is not designed for an instantaneous tube rupture; instead, the decision is made to remediate this event through a specific inspection program designed to target damage in the tube bundle that may be a result of flow-induced vibration or SCC mechanisms. The tube-to-tubesheet joints, typically strength welds, will also be analyzed to ensure that they meet minimum Code requirements to resist pullout.

If any of these analyses were to indicate the potential for an instantaneous full-bore tube rupture, overpressure protection for an instantaneous tube rupture should be provided. If they do not reveal any potential for instantaneous tube damage, further criteria must be met involving inspection techniques and programs.

Following the API 521 guidelines, the inspection techniques, including their comprehensiveness and frequency, must be appropriate for the exchanger's service and materials of construction. The inspections should not find any evidence of thinning or cracking that could lead to a full-bore tube rupture. If any past or future inspection shows potential damage that could lead to an instantaneous full-bore rupture, suitable pressure relief must be provided.

TUBE VIBRATION ANALYSIS

Heat exchanger tube vibration analysis is performed to determine the susceptibility of the tubes to flow-induced and acoustical vibration, along with the cracking and fretting damage that may occur as a result. The methods used are in accordance with the Standards of the Tubular Exchanger Manufacturers Association (TEMA) and are supplemented by the methods presented by HTRI [3]. The vibration criteria evaluated include checks on the following vibration mechanisms:

a) Fluidelastic Whirling/Instability

This phenomenon is characterized by large amplitude random vibration of tube arrays. Above a critical flow velocity, the damping of the tubes/supports cannot dissipate the energy in the flow stream, and the tubes begin to vibrate in an orbital manner. As a result, baffle fretting and tube mid-span collisions can occur. In this assessment, the calculated critical velocity is compared to the shellside crossflow velocity. Good design would suggest keeping the crossflow velocity well below the critical velocity.

b) Vortex Shedding

As flow crosses over tubes, vortices are set up on the backside of the tubes. These vortices can result in large amplitude resonant vibration if the vortex shedding frequency is close to the natural frequency of the tubes. This vortex phenomenon is typically not likely to occur deep inside a tube bundle; however, it can affect tubes located on the perimeter of the bundle. Good design requires that the calculated vortex shedding frequency be at least 20% away from the natural frequency of the tubes. In the assessment, the amplitude of tube vibration is compared to acceptable vibration amplitudes for various tube diameters and pitch orientations. For this mechanism, even though vibration may be predicted, if the amplitude of vibration is below acceptable limits, damage is not expected.

c) Tube Collision Parameters

The tube collision amplitudes are based on a force balance between flow over the tubes and the forces restraining the tubes in the baffle holes. The parallel flow amplitude and the crossflow amplitude, if exceeded, predict the likelihood that adjacent tubes will collide at their mid-span. Tube failure with these mechanisms is a strong function of fatigue and the endurance limit of the tube material.

d) Acoustic Vibration

Acoustic vibration can occur when the shellside fluid is a vapor or gas. The characteristic frequency of acoustic vibration in a heat exchanger is dependent on the shell diameter and the velocity of sound in the shellside fluid. The acoustic frequency can become excited by either vortex shedding or turbulent buffeting (caused by the fluid forcing frequency). The resultant acoustic vibration can lead to tube damage when the acoustic frequency is in resonance with the tubes.

BUNDLE AND SHELL ENTRANCE AND EXIT VELOCITIES

TEMA requires the values of the dynamic pressure (ρv^2) value to be checked at the bundle and shell entrance and exit areas. The dynamic pressure is a typical measurement for momentum, indirectly quantifying the kinetic energy of the moving fluid, and should meet the criterion shown in Equation (1) to minimize the potential for perimeter tube erosion:

$$\rho v^2 \leq \left[4000 \ \frac{lb_m}{ft \cdot s^2}\right] \qquad (1)$$

Failure of this screening criterion would not necessarily indicate an increased potential for full-bore tube rupture, since erosion is not a damage mechanism expected to occur instantaneously. Instead, this would likely occur over a longer period of time, and modifications to the inspection program geared toward erosion identification would sufficiently mitigate the situation.

TUBE-TO-TUBESHEET JOINT DESIGN

Tubes pulling out of the tubesheet will result in a similar event to tube cracking or tube rupture; two paths (orifices) of flow will result from the high-pressure to low-pressure side of the exchanger. The ASME Code provides criteria to assess the tube-to-tubesheet joint's ability to withstand the axial forces created by thermal and pressure differentials between the shell and the tubeside components. In most applications where there is a large pressure differential between the tubeside and the shellside of the exchanger, the tube-to-tubesheet joints will be strength-welded. Tube pullout is primarily a concern with fixed-fixed tubesheet exchanger designs. The U-tube design has inherent flexibility and, as a result, tubes are subjected to much lower axial stress. Rolled and expanded type joints are usually sufficient to negate pullout concerns for U-tube bundles; however, these should be checked as part of the TRCA.

In applications where the exchanger is subjected to frequent thermal and/or pressure cycles, a fatigue assessment of the tube-to-tubesheet joint should also be conducted.

METALLURGICAL AND CORROSION ANALYSIS

The focus for the Metallurgical and Corrosion analysis is mainly the determination of damage mechanisms that could lead to an instantaneous tube rupture, such as environmental SCC, brittle fracture, or creep. These damage mechanisms tend to result in failures that could occur instantaneously and significantly increase the probability of a full-bore tube rupture.

To a lesser extent, corrosion damage mechanisms are also evaluated to identify any past or future aggressive corrosion mechanisms that could potentially cause tube failures. This analysis includes consideration of issues associated with pitting and localized corrosion. In general, active corrosion mechanisms do not automatically increase the potential for an instantaneous full-bore tube rupture, since the damage tends to occur over a longer period. An appropriate inspection program coupled with leak detection systems provides adequate mitigation to eliminate the potential for an instantaneous full-bore tube rupture.

Figure 1 - Corroded heater tubes.

REVIEW OF BUNDLE INSPECTION PROGRAM

Selection of tube bundle inspection techniques depends on the tube material and the defect types expected. In general, inspection techniques suggested for the damage mechanisms of most concern for the tube rupture scenario are those that can detect flaws or defects due to environmental cracking, localized corrosion, and cracking damage at locations where the tubes come in contact with the crossflow baffles. In addition, localized corrosion may occur in the stagnant area at the backside of the tubesheet at the tubeside inlet. The non-destructive testing (NDT) techniques available for inspection of tube bundles include conventional Eddy Current inspection (EC), full saturation EC, remote field EC, magnetic flux leakage, ultrasonic IRIS, and laser optics. Each of these NDT techniques has advantages and limitations. For example, conventional EC is very sensitive to pits and cracks but is limited to non-ferromagnetic materials. IRIS is accurate in measuring wall thickness, but it will miss small defects such as pin-holes and cracks. Optical techniques are limited to ID defects. NDT techniques are continually evolving, and it is extremely important that the guidance of a knowledgeable NDT practitioner be obtained. Proper selection of the NDT techniques is key to suitable inspection of heat exchanger tubes.

Note that the quality of the results from EC and other testing techniques is very dependent on the operator of the equipment. It is strongly suggested that operators are sufficiently trained and have demonstrated their ability to locate defects on sample tubes that have known defects.

Also of importance is inspection of the tube-to-tubesheet joint and tubesheet ligaments using PT inspection. This is particularly important when the exchanger is exposed to mechanical and/or thermal cycles that could result in fatigue cracks. Fixed-fixed tubesheet exchangers are more prone to this type of damage than are exchangers that utilize floating heads or U-bends.

USE OF LEAK DETECTION SYSTEMS

For corrosion-related damage mechanisms, the use of leak detection systems can provide significant early warning to operators so that the potential of an instantaneous tube rupture can be greatly reduced. The use of leak detection systems for exchangers is recommended in services that have aggressive corrosion mechanisms. Leak detection becomes even more important when the low-pressure side is a closed system, such as a demineralized cooling water system.

WHAT SETS E^{2}G APART?

Principal Engineer, Phil Henry, P.E., serves as Task Force Chair for API 520. He is world renowned and his expertise sought after to solve the most challenging problems our clients face. He and his team of SMEs have years of practical experience and understand the nuances and history behind the requirements, providing them a unique perspective, which allows them to customize client solutions to mitigate risk while managing the investment. Our detailed process identifies numerous decision-making points throughout a tube rupture scenario that must be considered to identify the best course of action for the client's specific situation.

REFERENCES

[1] API Standard 521, *Pressure-relieving and Depressuring Systems*

[2] ASME Boiler and Pressure Vessel Code, Section VIII, Division 1

[3] Heat Transfer Research Institute (HTRI)

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