RAGAGEP Considerations for Relief and Flare Systems

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Recent emphasis on Recognized and Generally Accepted Good Engineering Practices (RAGAGEP) increased the scope of relief systems risk factors that require evaluation to develop complete and compliant Pressure Relief and Flare Systems documentation. Failure to comply with RAGAGEP ((d)(3)(ii)) is the most cited element of the Process Safety Management requirements.

This paper discusses how RAGAGEP considerations now require evaluation and proper documentation of risk factors that are often overlooked including but not limited to: dispersion analysis, thermal radiation, noise, vibration risk, reaction forces and structural supports, metal cold temperatures due to expansion cooling and two phase flow, hot temperatures due to fire exposure and/or runaway reactions, PRV stability, chemical reaction systems, and loss of high pressure/low pressure interface.

Important RAGAGEP considerations for these additional risk factors are highlighted and discussed. Recommendations are provided on how to best address these factors in the evaluation and documentation of design basis. © 2016 American Institute of Chemical Engineers Process Saf Prog 000: 000–000, 2016

Keywords: recognized and generally accepted good engineering practices; relief systems; flare systems

RAGAGEP

Recent updates to Recognized and Generally Accepted Good Engineering Practices (RAGAGEP) have expanded the scope of risk factors that require evaluation to develop complete Pressure Relief and Flare System (PRFS) documentation. Additionally, the United States Occupational Safety & Health Administration (OSHA) issued Standard Interpretation "RAGAGEP in Process Safety Management Enforcement" on June 8, 2015 with respect to the Process Safety Management (PSM) standard 29 CFR 1910.119.

In the Standard Interpretation, OSHA identifies three primary sources of RAGAGEP:

1. Published and widely adopted codes
2. Published consensus documents
3. Published non-consensus documents

Explicitly included in the three primary sources of RAGAGEP are industry standards and recommended practices such as American Society of Mechanical Engineers (ASME), National Fire Protection Agency, Center for Chemical Process Safety (CCPS), the Chlorine Institute (CI) guidelines, and applicable manufacturer's recommendations.

OSHA further clarifies "Appropriate Internal Standards" and the use of "Shall" and "Should" in RAGAGEP. The application of internal standards and the employer's decision to follow (or to not follow) RAGAGEP is expected to be made to meet or exceed the protective requirements of published RAGAGEP.

Failure to comply with RAGAGEP ((d)(3)(ii)) is the most cited element of the PSM requirements [1].

RISK FACTORS

When complying with the "relief system design and design basis" Process Safety Information (PSI) element of the PSM standard (1910.119(d)(3)(i)(D)), the traditional approach included application of ASME and American Petroleum Institute (API) standards. Relief devices were sized and installed per ASME and API 520. Overpressure scenarios were considered and relief requirements quantified in accordance with API 521. The primary goals of the analysis and documentation was to ensure that relief devices provided adequate capacity, that the inlet pressure drop and built-up backpressure were within recommended limits, and that the physical installation met the requirements (eliminate restrictions on the inlet line and absence of pockets in the discharge line, for example) [2,3].

There are several additional categories that require special attentions and are often overlooked when reviewing or establishing the design basis for relief and flare systems [1,4]. These categories are essential for compliance with RAGAGEP. They include but may not necessarily be limited to:

1. Dispersion analysis and safe discharge location
   a. Thermal radiation
2. PRV stability
3. Emergency relief systems piping
   a. Vibration risk
      1. Noise
   b. Reaction forces and structural support,
   c. Temperature excursions
      1. Cold metal temperatures due to expansion cooling and two phase flow
      2. Hot temperatures due to fire exposure and/or runaway reactions,
4. Other factors
   a. Reaction systems
   b. Loss of high pressure/low pressure interface and liquid displacement.

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Dispersion Analysis and Safe Discharge Location

In addition to the Environmental Protection Agency (EPA) regulations, such as 40 CFR 68 and 40 CFR 60, Subparts J & JA in particular, RAGAGEP include evaluating relief system dispersion characteristics.

API STD 521 recognizes that disposal to atmosphere can be safe and has been demonstrated. However, in accordance with §5.8.1 careful attention is required to ensure that atmospheric disposal of relief streams is safe. §5.8.2 and §5.8.3 provide further recommendations on the evaluation of the flammable and toxic hazards, respectively. Furthermore, API STD 520 Part II suggests that dispersion analysis may be used to evaluate the hazards associated with bellows valve bonnet venting.

Perhaps more importantly, the OSHA National Emphasis Programs (NEP; Directives CPL 03-00-010 and CPL 03-00-014) provide guidance for Compliance Safety and Health Officers (CSHO) when inspecting refineries and chemical facilities. While it is recognized that the Process Hazard Analysis (PHA) team is expected to identify any hazard associated with an atmospheric release, the actual dispersion assessment is often a recommendation from the finding.

The process data required for performing dispersion analyses is a readily available result of typical PRFS evaluation protocols. With the guidance and methodology provided in API STD 521, evaluating flammable and toxic hazards associated with an atmospheric relief should be included in any relief system design and design basis documentation [5].

Flame outs during flaring can lead to the dispersion of flammable, toxic, or environmental pollutants. During flame outs, flares will behave like dispersion stacks. Dispersion analysis should be conducted to ensure that any delayed ignition or non-ignition do not create hazardous conditions from thermal radiation (flame jets, vapor cloud fires), explosions, and/or toxicity or environmental impact.

In installations where relief devices are designed to discharge two-phase materials special care is required to assess delayed ignition explosion potential as well as toxicity impact. Many two-phase discharges will include liquid aerosols and these aerosols make the dispersion mixture heavier than air and increase the mass of the cloud. Note that two-phase discharges can also occur from oversized relief devices in vapor service where two-phase are present in the source vessel.

Liquid rainout represents a challenging problem for two-phase discharge directly to atmosphere. Rainout can occur if the droplets produced during thermal or mechanical break of the liquid/two-phase discharge from a relief device are large enough to settle out. If ignited, they can cause widespread fires and behave like flaming rain.

Hot hydrocarbon releases from relief devices discharging to atmosphere can condense and create mists. However, these mists will almost always remain airborne because they will be in the range of 10 microns. The presence of flammable mists or small droplets can substantially increase the explosion severity of the dispersing material if delayed ignition occurs.

The exit velocity, angle, and density of the discharged material from a relief device along with wind speed and direction will determine if the dispersing jet or cloud will touchdown at distances further than the location of the discharge. If the limiting concentration of interest is for odor threshold or toxicity limits, these touchdown downwind distances can be significant. See Figure 1.

Stack downwash can also be an issue with discharges from relief devices that are close or below roof lines. Stack downwash can exacerbate explosion potential if delayed ignition occurs and can present hazardous conditions for personnel within the confines of nearby structures [6]. Stack downwash is more pronounced when flows out of the relief system discharge piping are low with low velocities. Low flow velocities also lead to poor dispersion and more persistent dispersing clouds.

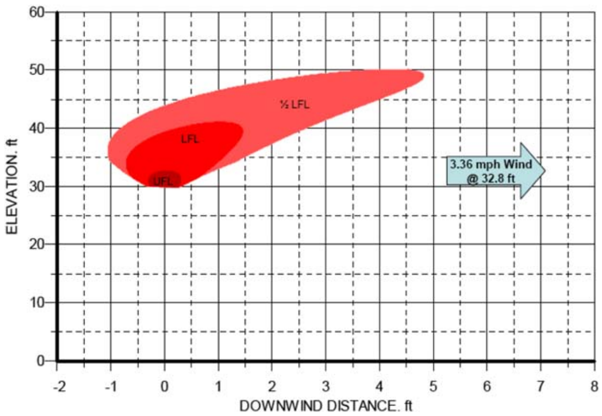

Figure 1. Dispersion analysis for PSM compliant documentation. [Color figure can be viewed in the online issue, which is available at **wileyonlinelibrary.com**.]

Environmental impact should be considered, especially in the case of two-phase discharges where rain-out of liquid droplets is possible.

Thermal Radiation

Thermal radiation from flare stacks as well as vent stacks and the atmospheric discharge of pressure relief devices should be considered for both personnel and equipment safety. Where flammable materials are discharged and ignition occurs (immediate or delayed), vent stacks will behave like flare stacks. See Figure 2.

There have been instances where flammable vapors being discharged to the atmosphere ignited due to static or lightning or the presence of nearby ignition sources from other equipment and hot surfaces or open flames. Immediate ignition can cause flame jets from momentum dominated discharges from pressure relief devices. Delayed ignition can cause vapor cloud fires and explosions followed by flame jets.

PRV Stability

Pressure Relief Valve (PRV) stability and the 3% "rule" has been under the limelight over the past several years as the subject of litigation, research, and modeling [7]. PRV instability is very rarely the cause of incidents leading to serious accidents. However, it is important to ensure that when the last line of defense is asked to perform, any relief devices operate in a safe and stable manner.

The 3% "rule" remains a recommendation and not a requirement in RAGAGEP. The "rule" appears in both ASME Boiler and Pressure Vessel Code Section VIII Division I (BPVC-VIII-I) Non-Mandatory Appendix M and as a "should" in API STD 520 Part II. However, based on OSHA's RAGAGEP interpretation, any deviation from a "should" item requires that the measure is "at least as protective, or that the published RAGAGEP is not applicable."

API practice formed the foundation of the ASME guidance. In the past API RP 520 Part II has allowed an "Engineering Analysis" to demonstrate that non-recoverable inlet pressure drop (IPD) greater than 3% of the set pressure

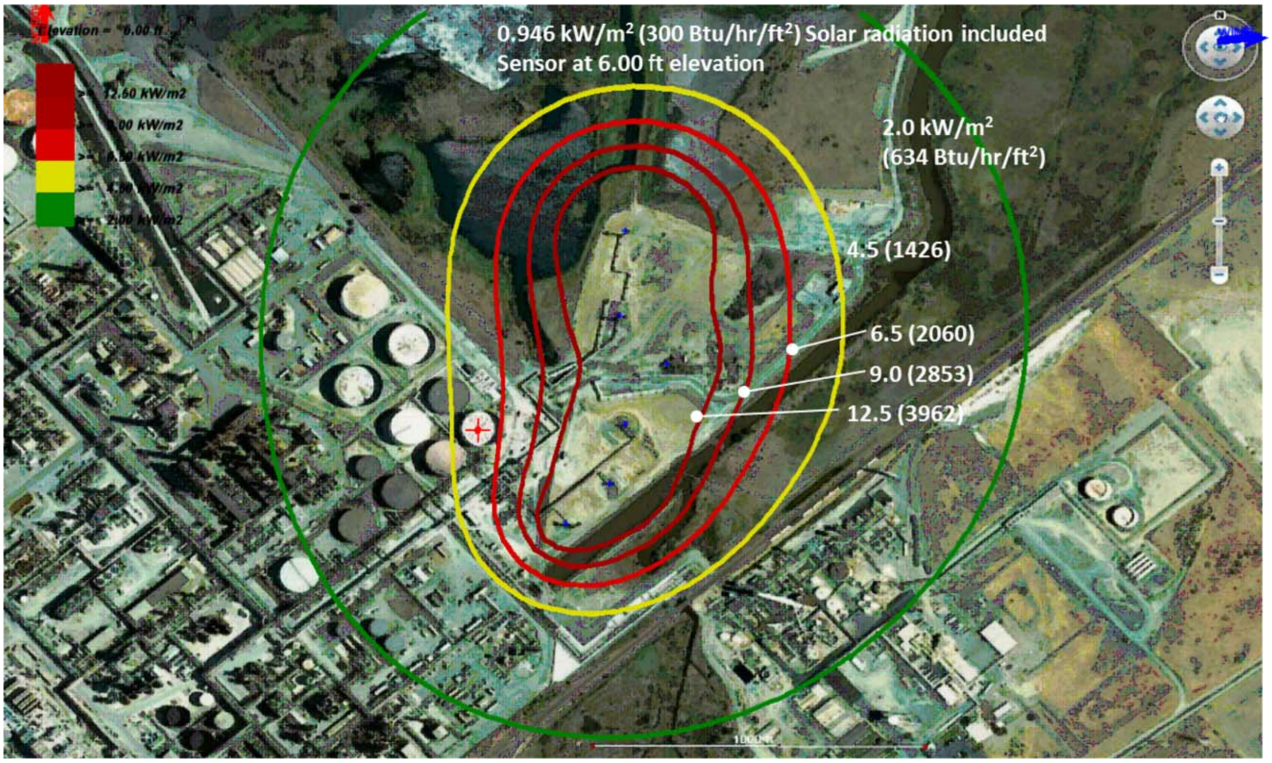

Figure 2. Thermal radiation due to ignition of atmospheric discharge. [Color figure can be viewed in the online issue, which is available at **wileyonlinelibrary.com**.]

is safe, but has been silent on a method. Based on significant research and experience, the 6th edition of API 520, now a Standard, includes an engineering analysis (§7.3.6) and provides valuable guidance to the reader [8,9].

Make no mistake, CSHOs are instructed to review PSI documentation with respect to the 3% "rule" (see CPL 03-00-010 §X.A.3.1). A prudent relief system design will incorporate the RAGAGEP available in API STD 520 Part II.

Excessive inlet line pressure loss or backpressure can cause PRV instability. Stable PRV installations are required by ASME and API. The governing case for PRV instability may be very different from the governing case for PRV flow capacity sizing or reaction forces for structural support.

The 3% inlet pressure loss rule is experience based and is not sufficient to guarantee PRV stability. The 3% inlet pressure loss rule does not directly address acoustic interaction between the valve disk and the fluid/piping system. See Figure 3. The 3% inlet pressure loss rule cannot be met for some simple installations even with a very short inlet pipe. It has been shown that installations with more than 3% inlet pressure loss can operate in a stable manner while installations with less than 3% inlet pressure loss can operate in an unstable manner. Stability may need to be assessed and confirmed for all credible scenarios and not necessarily just the one with the highest flow rate or the largest steady state reaction force. An engineering Analysis as defined by API 520 II should be considered even when the 3% inlet pressure loss rule is met.

PRV instability can occur due a variety of reasons and instability may occur with other than the dominant design scenario. This includes but is not limited to intermittent flow, excessive inlet pressure loss, excessive backpressure, body bowl choking, oversized pressure relief device, and condensing flow [10,11].

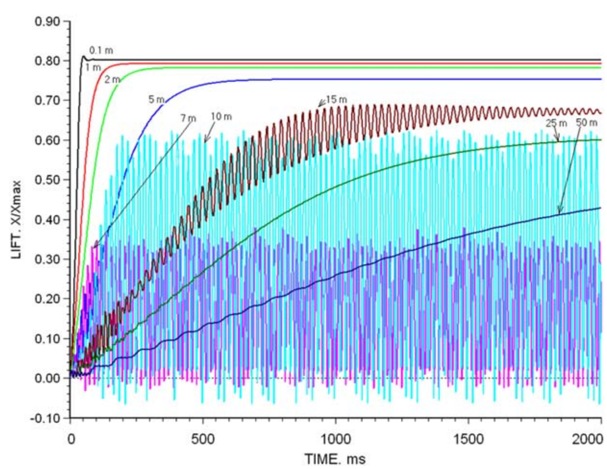

Figure 3. Excessive inlet loss or backpressure may cause PRV instability. [Color figure can be viewed in the online issue, which is available at **wileyonlinelibrary.com**.]

Emergency Relief Systems Piping

The emergency relief system (ERS) consists not only of the relief device (PRV, rupture disk, etc.), but also the attached inlet and discharge piping. In the same vein as PRV stability, it is important to ensure that the entire ERS, adequately and safely handles the effluent from an overpressure scenario.

In addition to meeting the aforementioned inlet pressure drop and built-up backpressure limits, additional relief

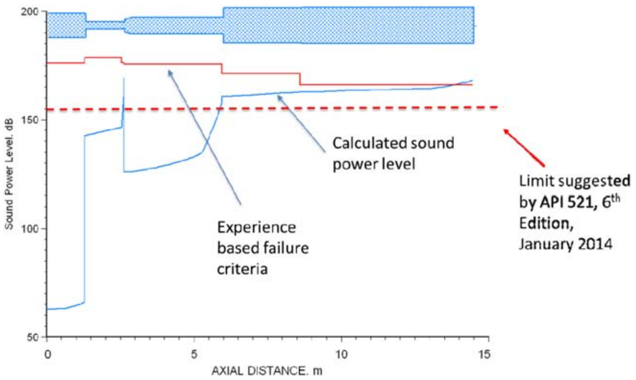

Figure 4. Vibration risk required per API 521. [Color figure can be viewed in the online issue, which is available at **wileyonlinelibrary.com**.]

system design basis documentation criteria, in accordance with RAGAGEP, include:

1. Vibration Risk,
2. Reaction Forces, and
3. Temperature Excursions (hot and cold)

ASME BPVC-VIII-I Non-Mandatory Appendix M (M-7) requires consideration that discharge line vibration is considered minimized. Furthermore, API STD 521 §5.5.12 discusses acoustic fatigue and recommends a method to calculate the sound power level (SPL). For SPL greater than 155 dB further modeling is recommended to evaluate the risk. Experience has shown that the high velocities and pressure drop encountered in many relief system piping designs may fail to meet the 155 dB criteria; for these situations, mitigation options are provided in §5.5.12.3. See Figure 4.

Large high-pressure relief devices may generate the thrust of a jet engine when they open! RAGAGEP requires that the relief system piping is adequately designed, braced, and supported to accommodate the static and dynamic loads. Reaction forces in relief system piping are evaluated in accordance with ASME B31.3 and API STD 520 Part II §5.8.2. ASME BPVC-VIII-I Non-Mandatory Appendix M (M-12) recommends evaluating the bending moments and stresses for both steady-state flow and transient dynamic loads upon relief device opening. API STD 521 provides guidance on reaction forces in §5.5.14 with respect to disposal systems and includes reaction forces in the list of recommended minimum relief system design documentation in §4.7.3.9 item e.

Another risk factor in ERS piping design is low temperature. Most often associated with two-phase or condensing flow in relief device discharge lines, but also experienced due to all-vapor relief, low temperature may result in embrittlement. Auto-refrigeration, low-temperatures, and selecting appropriate discharge piping mechanical design limits are discussed in API STD 521 §5.5.13.2 with cautions related to fluid properties found in §5.2 and §5.2.2.4. OSHA Directive CPL 03-00-010 instructs CSHOs to evaluate piping circuits and ensure the PSI includes the materials of construction. Although often associated with the Mechanical Integrity PSM element, ERS piping materials of construction are easily evaluated by a prudent PRFS designer [12].

When evaluating ERS piping, it is critically important to consider the solution methodology. Traditional approaches such as Crane Technical Paper No. 410 and "L/D" hydraulic calculations were developed based on Newtonian liquids and typical steady-state flow rates, which are not necessarily appropriate for high-pressure, high-velocity vapor, highly viscous liquid or two-phase relief [13]. These simplified techniques, including isothermal assumptions, may not capture choke points and fluid expansion or contraction that result in excessive reaction forces, acoustic vibration risk, and low temperature concerns, which are required to be evaluated by RAGAGEP [14].

Vibration Risk

The assessment of fatigue failure due to vibration risk is now required by API-521. Fluid flow in pipes generates turbulent energy (pressure fluctuations). Dominant sources of turbulence are associated with flow discontinuities in the piping systems (e.g., partially closed valves, short radius, mitered bends, tees or expanders). The level of turbulence intensity is a function of pipe size, fluid density, viscosity, velocity, and structural support. High noise levels are generated by high velocity fluid impingement on the pipe wall, turbulent mixing, and if the flow is choked, shock waves downstream of flow restriction, which leads to high frequency excitation/vibration [15].

Fatigue failure of relief and/or process piping caused by vibration can develop due to the conversion of flow mechanical energy to noise. Factors that have led to an increasing incidence of noise vibration related fatigue failures in piping systems include but are not limited to (a) increasing flow rates as a result of debottlenecking which contributes to higher flow velocities with a correspondingly greater level of turbulent energy, (b) frequent use of thin-walled piping which results in higher stress concentrations, particularly at small bore and branch connections, (c) design of process piping systems on the basis of a static analysis with little attention paid to vibration induced fatigue, (e) and lack of emphasis of the issue of vibration in piping design codes. Piping vibration is often considered on an ad-hoc or reactive basis. According to the UK Health and Safety Executive (HSE), 21% of all piping failures offshore are caused by fatigue/vibration. Typical systems at risk include large compressor recycle systems and high capacity pressure relief depressuring systems. For relief and flare piping, flow induced turbulence and high frequency acoustic excitations are key concerns [16].

Excessive AIV/FIV can cause piping and equipment failures. Even when complete failure of the piping does not occur, excessive AIV/FIV can cause cracks allowing air ingestion/ingress into flare and vent systems creating an explosion hazard. Use of equivalent pipe length methods for fitting losses can lead to inaccurate estimates of sound power levels that are required to assess vibration risk. High superimposed constant backpressure can reduce the value of sound power level from AIV/FIV sources including those that are from pressure relief systems.

Reaction Forces

Reaction forces are not always properly calculated and documented. Dynamic loads and dynamic load durations vs. structural response time for piping need to be considered. See Figure 5. How long does it take to fill the discharge pipe for a relief system for example? Reaction forces can be different for different pressure relief device types, rupture disks vs. modulating or pop action pressure relief valves. The design case for reaction forces may be different than the governing case for relief device flow capacity. The use of equivalent pipe length methods for fitting losses can lead to inaccurate estimates of reaction forces especially for gas and multiphase flow. Safe upper limits for reaction forces can be established by neglecting the attached relief piping to the relief device, especially where rupture disks are the primary relief device.

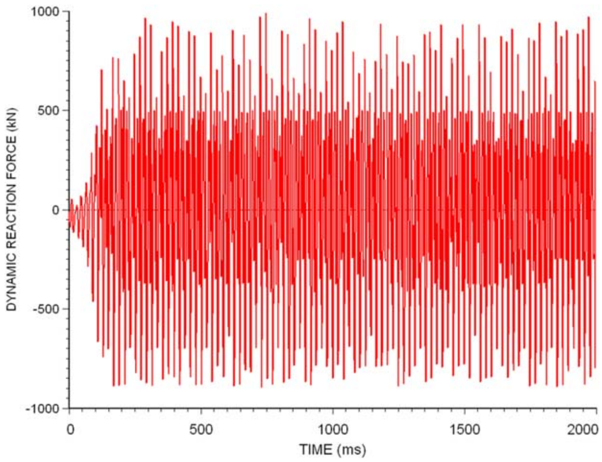

Figure 5. Properly calculate and document reaction forces. [Color figure can be viewed in the online issue, which is available at **wileyonlinelibrary.com**.]

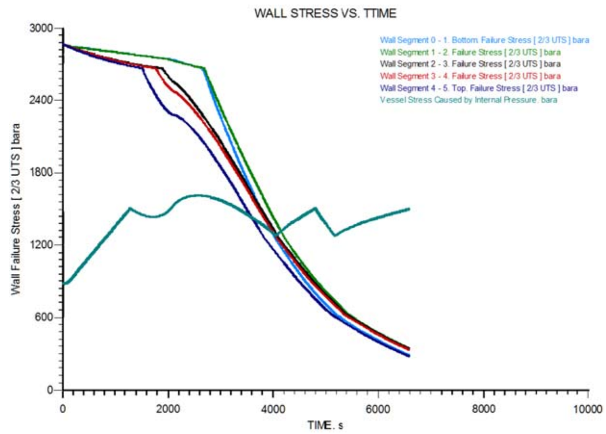

Figure 7. Temperature excursions can cause metal failures. [Color figure can be viewed in the online issue, which is available at **wileyonlinelibrary.com**.]

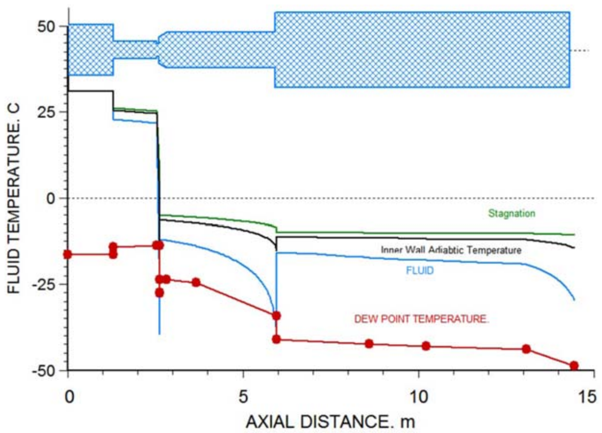

Figure 6. Low temperature downstream of an expansion. [Color figure can be viewed in the online issue, which is available at **wileyonlinelibrary.com**.]

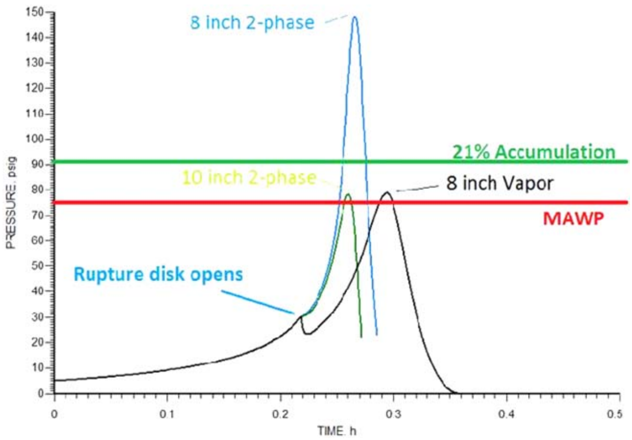

Figure 8. Proper selection of vessel hydrodynamics and relief phase. [Color figure can be viewed in the online issue, which is available at **wileyonlinelibrary.com**.]

Special considerations must be given to dynamic reaction forces from pressure relief devices in liquid service or high pressure systems. These systems can lead to substantial pressure spikes and reaction forces during fluttering and/or chattering than loosen bolts and damage piping with potential loss of containment.

Temperature Excursions

Excursions in temperatures, hot or cold, can lead to metal failure. Cold temperatures caused by expansion cooling can lead to embrittlement. Piping and equipment downstream of the expansion point, typically the flow limiting area, can be at fluid temperatures if condensation occurs. Piping and equipment downstream of the expansion point can collect cold liquids from condensation when it occurs [12,14].

Hot temperatures caused by fire or flame jet impingement or runaway reactions can lead to weakening of the metal strength and subsequent metal failure. See Figure 7. Hot temperatures due to flame jet or pool fire impingement or flame radiation can cause vessel failure at the reseat point of the PRV if the fire duration is long enough [17–19].

For gas flow the inside pipe wall metal surface temperature can be higher than the fluid temperature especially when the flow velocity is high. See Figure 6. Use of equivalent pipe length methods for fitting losses can lead to inaccurate estimates of pipe metal temperatures for gas flow and multiphase flow because of how single and multiple choke points can be miscalculated [12].

Other Factors

Reactive Chemicals

Reaction systems require a higher level of care and design basis documentation. Relief systems design and evaluation where reactive chemicals are involved is more about chemistry (desired and undesired) than it is about fluid mechanics. A key element that is often missed is the correct reaction system characterization under runaway conditions. Scenarios leading to runaway reactions need to be considered and the potential for two-phase flow from pressure relief devices must be considered as well. See Figure 8.

Two phase flow will almost always occur during runaway reactions. The dispersion and/or effluent handling of reaction products which may include toxics and/or flammable should also be considered. We note that runaway reactions will often continue in the discharge piping and effluent handling systems [20–24].

Loss of *H*igh *P*ressure/*L*ow *P*ressure Interface and Liquid Displacement

The loss of high pressure (HP)/low pressure (LP) interface is often poorly evaluated and in some cases missed all together. The loss of HP/LP interface should be evaluated to (a) ensure that the downstream equipment can handle the energy and/or mass accumulation and (b) to also ensure that the upstream equipment can handle the rapid depressurization. The loss of the HP/LP interface can occur as a result of automatic controls failure/malfunction, and/or inadvertent valve opening/human error [25,26]. Potential outcomes of the loss of the high pressure/low pressure interface include but may not necessarily be limited to:

- Overfilling of the downstream equipment, i.e. as the liquid is displaced from the upstream equipment into the downstream equipment and the resulting high pressure associated with liquid overfilling of the downstream equipment
- High temperatures associated with the rapid compression of the vapor space of the downstream equipment associated with liquid displacement,
- Multiphase flow associated with increasing liquid level, liquid entrainment, and/or high superficial vapor velocities caused by pressure relief device actuation in the downstream equipment,
- Low temperatures caused by rapid depressurization in the upstream equipment and ultimately in the downstream equipment as pressure is further reduced when the gas breaks through to the downstream equipment,
- Possible hydrate formation in the upstream and/or downstream equipment

CONCLUSION

Recent industry experience and research has resulted in additional guidance in standards, recommended practices, and other RAGAGEP. OSHA's timely interpretation of RAGAGEP warrants that PRFS design and design basis calculations and documentation expand to meet what were formerly considered unessential requirements. The recent emphasis on RAGAGEP raises the bar for relief systems design and evaluation studies.

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