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Statistical Analysis of Site-wide Relief Systems Study and the Deficiencies That Were Identified

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Introduction:

This paper covers the credible typical mitigation options available to resolve inadequate pressure relief and flare systems. Typical reasons of inadequacy for pressure relief and flare systems are presented and common mitigation options for those inadequacies are covered. Then, examples of uncommon and unique mitigation options are provided including options such as advanced calculations and pressure relief valve stability analysis.

Overview:

The process safety world is constantly changing and evolving, and rightfully so. When considering pressure relief and flare systems, there are several areas where there are ongoing developments:

- New calculation methods
- Regulatory codes and standards
- Lessons learned

New calculation methods are constantly being developed or enhanced to address both new and existing safety subjects and issues. A few examples of this include:

- Two-phase Flow – the Design Institute for Emergency Relief Systems (DIERS) has made two-phase flow one of its main areas of focus. DIERS spent $1.6 million to investigate the two-phase vapor-liquid onset / disengagement dynamics and the hydrodynamics of emergency relief systems. Of particular interest to DIERS was the prediction of two-phase flow venting and the applicability of various sizing methods for two-phase vapor-liquid flashing flow.
- Runaway Reactions – in addition to progressing two-phase flow modeling, DIERS has also continued to develop and improve modeling of runaway reaction scenarios. Over the years, more sophisticated reaction models have been developed to allow more accurate prediction and modeling of runaway reactions.

- Pressure Relief Valve Stability – new engineering analyses have been developed through American Petroleum Industry (API) research groups, to further study pressure relief valve stability beyond the 3% irrecoverable inlet line loss criteria. This research has demonstrated that pressure relief valves can function stably above 3%, and provides an accepted methodology to determine and demonstrate stable operation of a pressure relief valve exceeding 3% irrecoverable inlet pressure losses.
- Acoustic Induced Vibration - Acoustic Induced Vibration (AIV) is generally applicable to lines in gas service, where large amounts of high frequency acoustic energy can be generated by a pressure reducing device such as a pressure relief valve. The flow rate and pressure primarily govern the amplitude of this energy drop through the piping system. Excitation due to this can lead to fatigue failure of welded downstream connections. Piping downstream of Pressure reducing devices as below is prone to Acoustic Induced Vibration AIV; with failures potentially occurring at small bore branches. It is important to consider this phenomenon when designing pressure relief systems piping; as mitigation options exist to prevent AIV from occurring.

Regulatory codes and standards are being updated continuously resulting in both new and stricter requirements. For example:

API Standard 520 Part I - This standard applies to the sizing and selection of pressure relief devices used in refineries, chemical facilities, and related industries for equipment that has a maximum allowable working pressure (MAWP) of 15 psig (103 kPag) or greater. The pressure relief devices covered in this standard are intended to protect unfired pressure vessels and related equipment against overpressure from operating and fire contingencies.

Part 1 of this standard was updated in 2014, and includes basic definitions and information about the operational characteristics and applications of various pressure relief devices. It also includes sizing procedures and methods based on steady state flow of Newtonian fluids.

Pressure relief devices protect a vessel against overpressure only; they do not protect against structural failure when the vessel is exposed to extremely high temperatures such as during a fire.

API Standard 520 Part II - This standard was updated in 2015, and was also changed from a Recommended Practice to a Standard. It covers methods of installation for pressure relief devices in gas, vapor, steam, two-phase, and incompressible fluid service.

API Standard 2000 – This standard covers the normal and emergency vapor venting requirements for aboveground liquid petroleum or petroleum products storage tanks and aboveground and underground refrigerated storage tanks designed for operation at pressures from full vacuum through 103.4 kPa (ga) (15 psig). It was updated in 2014, and discusses causes of overpressure and vacuum; determination of venting requirements; means of venting; selection and installation of venting devices; and testing and marking of relief devices.

> This standard applies to tanks containing petroleum and petroleum products, but it can also be applied to tanks containing other liquids; however, it is necessary to use sound engineering analysis and judgment whenever this standard is applied to other liquids. This standard does not apply to external floating-roof tanks.
>
> **Other** – OSHA's Refinery National Emphasis Program and PSM Covered Chemical Facilities National Emphasis Program included focus on ensuring pressure relief systems design documentation was kept up-to-date and accurate and resulted in an increased focus on pressure relief systems.

Safety incidents experienced in plant operation lead us to rethink assumptions used in process safety, such as which pressure relief scenarios are considered credible. Some examples include:

BP Texas City (2005) – A major incident occurred at the BP refinery in Texas City, Texas in March 2005. An explosion occurred when hydrocarbon vapors overflowed from a blowdown stack and ignited. The explosion resulted in 15 fatalities and 180 injuries. One of the contributing factors in this incident was the use of an inadequately designed Blowdown Drum and Stack as part of the pressure relief and venting system for the Raffinate Splitter, which had gone through several design and operational changes and was located close to uncontrolled areas.

Sonat Exploration Company (1998) - On March 4, 1998, a catastrophic vessel failure and fire occurred at a facility owned by Sonat Exploration Co in Louisiana. Four workers who were near the vessel were killed, and the facility sustained significant damage. The vessel lacked a pressure relief system and ruptured due to overpressurization during start-up, releasing flammable material which ignited.

First Chemical (2002) - On October 13, 2002, a violent explosion occurred in a chemical distillation tower at First Chemical Corporation in Pascagoula, Mississippi, sending heavy debris over a wide area. Three workers in the control room were injured by shattered glass. One nitrotoluene storage tank at the site was punctured by explosion debris, igniting a fire that burned for several hours. During the incident investigation conducted by the Chemical Safety Board (CSB), it was determined that the capacity of the PSV was inadequate to prevent overpressurization and catastrophic failure of the column.

Goodyear (2008) - On June 10, 2008, Goodyear operators closed an isolation valve between the heat exchanger shell (ammonia cooling side) and a pressure relief valve to replace a burst rupture disk under the pressure relief valve that provided over-pressure protection. Maintenance workers replaced the rupture disk on that day; however, the closed isolation valve was not reopened.

On the morning of June 11, an operator closed a block valve isolating the ammonia pressure control valve from the heat exchanger. The operator then connected a steam line to the process line to clean the piping. The steam flowed through the heat exchanger tubes, heated the liquid ammonia in the exchanger shell, and increased the pressure in the shell. The closed isolation and block valves prevented the increasing ammonia pressure from safely venting through either the ammonia pressure control valve or the rupture disk and pressure relief valve. The pressure in the heat exchanger shell continued climbing until it violently ruptured, killing one operator and causing extensive damage.

John Bresland, then Chairman of the CSB was quoted as saying "This tragic accident is but the latest example of the destruction that can result from a lack of effective pressure relief systems and practices".

Williams Olefins (2013) - On June 13, 2013, a catastrophic equipment rupture, explosion, and fire occurred at the Williams Olefins Plant in Geismar, Louisiana, which killed two Williams employees. The incident occurred during nonroutine operational activities that introduced heat to an offline reboiler, creating an overpressure event while the vessel was isolated from its pressure relief device. The introduced heat increased the temperature of the liquid propane mixture1 confined within the reboiler shell, resulting in a dramatic pressure rise within the vessel due to liquid thermal expansion. The reboiler shell catastrophically ruptured, causing a boiling liquid expanding vapor explosion (BLEVE) and fire.

These incidents were all investigated by the CSB and are a small snapshot of incidents which had some relation to pressure relief systems, as identified in the CSB reports.

Additionally, to meet the demands of the ever-changing safety world, we must seek to understand two issues:

- Quality of current safety systems
- Effectiveness of mitigation options to address inadequate design

Unfortunately, process safety can often be a victim of plant economics - time and money are not always available to instantly address every safety issue. Hence prioritization is necessary. A sample study of pressure relief systems can be utilized to create a picture of where the plant stands on a whole – just like an audit; and enable prioritization of pressure relief systems which are deemed to pose a greater risk to the facility.

Pressure Relief Systems Study Background

One process unit within a petrochemical facility which manufactures ethylene and propylene was chosen to be included in this study. In all, a total of 124 pressure relief systems and 198 pressure relief calculations were analyzed in this study.

Pressure relief systems were judged to be adequate or inadequate based on the following issues:

- Pressure relief requirement compared to relief capacity
- Irreversible inlet line loss (3%)
- Backpressure (10% for conventional, manufacturer specific for others)
- Installation/Code violation issues
- Temperature concerns

Of the 124 systems and 198 calculations analyzed, 85 systems (68.5%) and 135 calculations (68.2%) were found to be inadequate respectively

The pressure relief scenario calculations were found to be inadequate for the following reasons:

- Relief Capacity: 79 cases (40.9%)
- Irreversible Inlet Line Loss: 62 cases (32.1%)
- Backpressure: 43 cases (22.3%)

Overpressure scenarios which were most commonly found to result in an inadequately sized relief system include:

- Blocked Outlet – this was due to the pressure relief consequences not being considered during operational changes, such as increased plant throughput and increased operating temperatures
- Abnormal Flow – this was due to the original design neglecting consideration of a significant amount of manual valve operation overpressure scenarios, such as inadvertent opening of a control valve bypass valve.
- Thermal Expansion – this was due to the original design not considering thermal expansion to be credible, even for heat exchangers with high heat duty.
- Tube Rupture – this was due to the original design being inconsistent regarding consideration of tube rupture as a credible source of overpressure. The original design did not consider the mixing effects such as flow of a volatile mixture to the hot side of the exchanger.

External Fire and Control Valve Failure were found to result in very few inadequately sized systems, even though these two overpressure scenarios were commonly analyzed in the sample pressure relief systems.

Several causes were identified that contributed to the number of inadequate pressure relief calculations:

- Original design work did not consider specific pressure relief scenarios
- Missing or conflicting sources of data
- Changes in plant throughput and operating conditions
- Changes regarding compliance and company guidelines

Approximately 70% of the pressure relief systems analyzed were found to have an issue of some sort. Most of these issues consisted of interconnecting valves between equipment not being locked or car-sealed open which were easily resolved. However, there was also significant amount of relief systems that had installation issues which were not as easily mitigated:

- Pressure relief valves set above Maximum Allowable Working Pressure (MAWP)
- Low points in the pressure relief valve outlet line

Unprotected equipment was evaluated to determine if there was an applicable overpressure scenario in the revalidation study. An equipment item was considered “unprotected” if it did not have a free path to a pressure relief device, as defined by both API and ASME requirements. There were thirty-two pieces of unprotected equipment identified, of which twenty were found to require pressure relief protection as an applicable overpressure scenario was identified for these twenty pieces of equipment. The remaining twelve pieces of equipment were found to not have a credible overpressure scenario and did not require overpressure protection as the equipment was not designed according to ASME Section VIII.
Equipment which was considered unprotected was broken down into the following:

- Pumps: 15 identified (5 inadequate)
- Heat Exchangers: 11 identified (11 inadequate)
- Other: 6 identified (4 inadequate)

Several systematic deficiencies with the previous pressure relief system design work were identified:

- Pressure relief valves set above MAWP for system with only fire applicable
- Pressure relief common inlet and outlet piping not considered for hydraulic calculations
- Thermal relief valves often assumed to be adequate without proper evaluation of the applicable overpressure scenarios
- Some overpressure scenarios were not considered
- Manual/Bypass Valve Opening

None of the existing documentation for the pressure relief devices evaluated met the current documentation requirements given by API Standard 521, Section 4.7. For example, the existing documentation did not provide rationale regarding the credibility of all typical overpressure scenarios.

Mitigation Options

Typical Fixes:

When an existing pressure relief system design is found to have issues, there are many well-known and accepted “typical fixes”. These include:

Inadequate capacity:

- Installation of larger pressure relief valve
- Installation of additional pressure relief valve
- Mitigation of controlling scenario (e.g. fireproof insulation for an external fire scenario)

Excessive Inlet Pressure Losses:

- Reduce the number of fittings, elbows, etc.
- Use larger inlet piping

- Increase pressure relief valve blowdown
- Installation of a pilot relief valve

Excessive Outlet Pressure Losses:

- Reduce the number of fittings, elbows, etc.
- Use larger outlet piping
- Installation of a bellows relief valve

Temperature Concerns:

- Temperatures above Maximum Allowable Working Temperature: Fireproof insulation or water sprays for external fire scenario
- Temperatures below Minimum Design Metal Temperature: Select alternate Material of Construction

However, it should be noted that any of these “typical” fixes do not take into account cost – and indeed may be cost-prohibitive, especially for existing facilities. Therefore, prior to making any physical modification in the facility, it is worth ensuring that every design option has been considered thoroughly. Engineering design options will tend to be a fraction of the cost of any physical modification in the plant. Several mitigation options exist to address the inadequate pressure relief system calculations, including the following:

Administrative changes (ex: locking a bypass valve closed):

The opening of normally closed manual valves contributed significantly to the number of inadequate calculations and systems; particularly control valve bypass valves and steam out-valves.
Locking closed manual valves that are normally closed results in eliminating 18 inadequate pressure relief calculations of the 135 originally identified. Locking these valves closed affects more than just the pressure relief area sizing – with the scenario eliminated, there is no longer a need for any inlet and outlet pressure loss calculations for that scenarios.

API Standard 521 allows the use of Administrative Controls to mitigate or eliminate overpressure scenarios, particularly if the accumulated pressure does not exceed the corrected hydrotest. Specific guidance is given in API Standard 521 for the following scenarios:

- Closed outlets on vessels
- Inadvertent valve opening
- Check valve leakage or failure
- Heat transfer equipment failure (tube rupture)

Locating missing data/documentation:

Missing data was not found to be a significant factor in the sample size of pressure relief systems regarding pressure relief area sizing, with only one control valve sizing calculation, in the sample found to be inadequate for pressure relief area.

However, conflicting data resulted in several inadequate pressure relief systems design as conservative assumptions were used in cases where discrepancies existed for:

- MAWP of equipment – Up to date equipment documentation was not available for all equipment analyzed, resulting in inefficiencies, and discrepancies between original equipment U-1 forms and nameplates and the more recently updated P&IDs and PFDs.
- Normal/Design heat duty of exchangers – changes in operation resulted in simulation normal heat duties greater than the original design heat duty of exchangers, which lead to increased pressure relief requirements for scenarios involving heat transfer, such as blocking in the cold side of the exchanger.
- Operating conditions (vapor vs liquid system) - changes in operational procedure resulted in flow through several systems condensing to liquid phase from the originally designed vapor flow; however, the design of the pressure relief devices and pressure relief piping layouts were not updated to accommodate the change to liquid flow.

The amount of information needed to meet the OSHA 1910.119 PSI element can be considerable. There is no requirement that all PSI be compiled in a single document, or that it be located in a single file. Where it is contained in various documents and/or locations, good practice is to compile an index of the PSI and/or locations.

During the National Emphasis Program audits, conducted by OSHA, inadequate or outdated Process Safety Information was commonly one of the most frequently cited elements.

In the case of pressure relief systems, this can cause inefficiencies, additional costs, and most importantly, the potential for improper relief system design.

Advanced calculation methods – Dynamic Simulation

Improvements in computational power and software have led to increased availability of dynamic relief sizing calculations

Various different relief scenarios can be modelled dynamically:

- External Fire
- Loss of Cooling
- Tube Rupture
- Vapor Breakthrough / Liquid Displacement

Benefits of a dynamic pressure relief system simulation include calculating a more accurate representation of the system at relief conditions, typically resulting in decreased pressure relief flowrate requirements and required relief areas; and hence potentially smaller pressure relief valves.

Additionally, dynamic simulations enable the user to calculate the effects of relief on upstream and downstream systems, such as the ability to compute changes in flow in and out of the system due to changes in pressure and temperature over time.

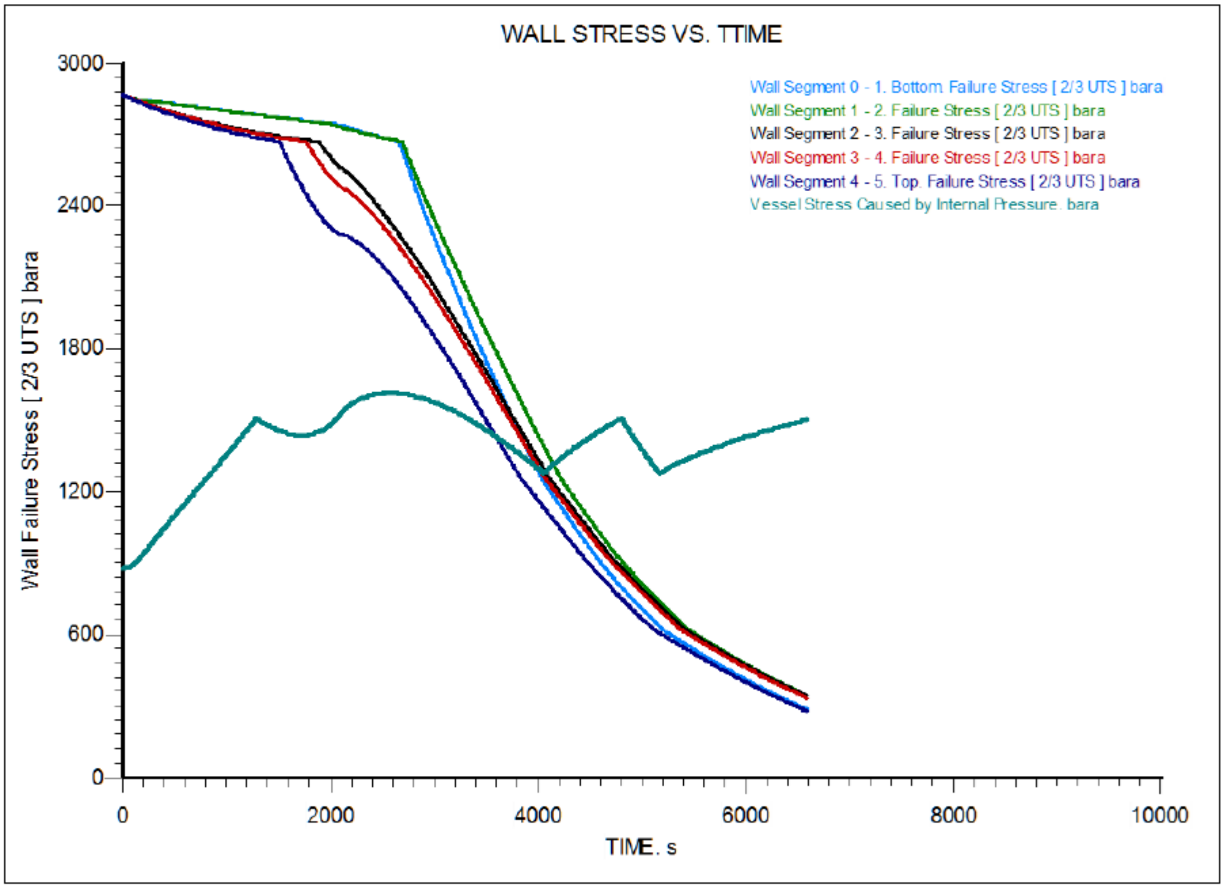

Figure 1 – Example of Dynamic Simulation to Predict Vessel Wall Failure Due to Fire Exposure

Advanced Modeling – Pressure Relief Valve Stability Analysis

Pressure Relief Valve (PRV) stability and the 3% "rule" has been under major focus over the past several years as the subject of litigation, research, and modeling. 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 pressure 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 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.

While the previous mitigation options may have primarily addressed pressure relief system capacity inadequacies, the irreversible inlet loss inadequacies can still remain a concern. The Force Balance method can be used to determine if a pressure relief device installation will behave in a stable manner, even when inlet pressure losses exceed 3%.

- Inlet and outlet piping configuration highly impacts stability
- Irrecoverable inlet loss from friction has little impact

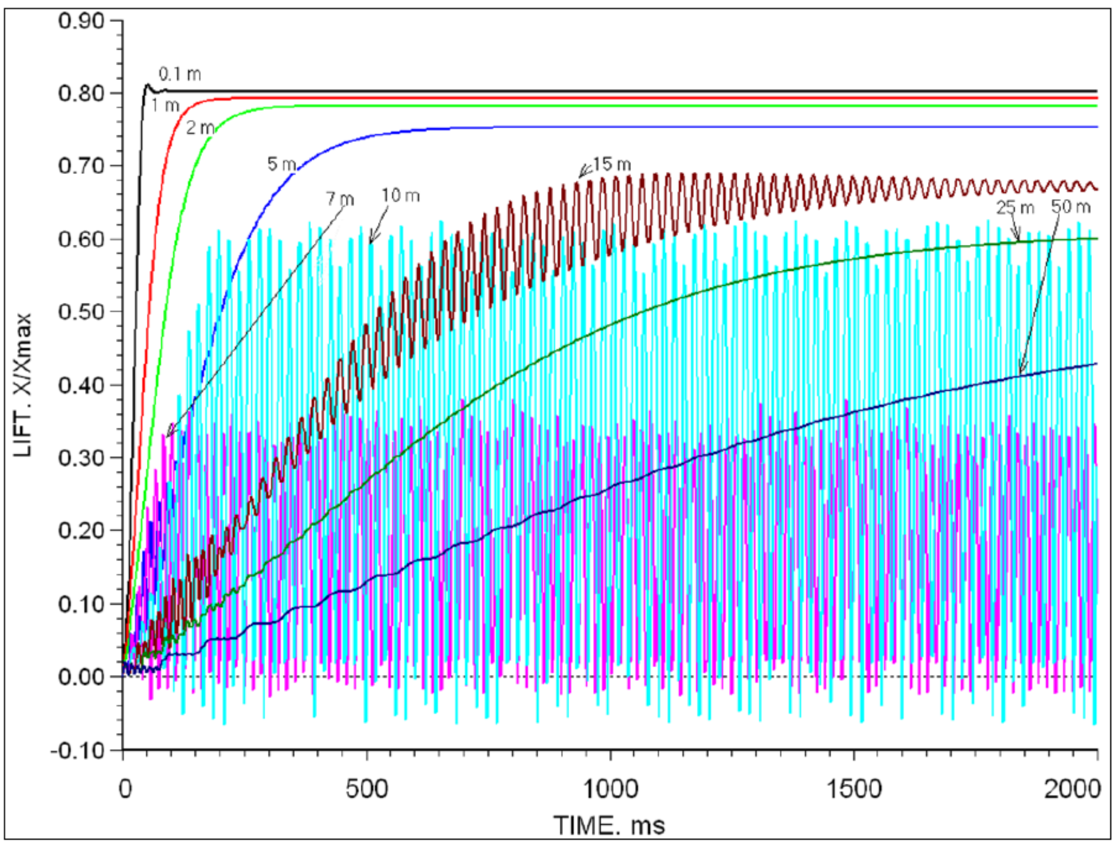

Figure 2 – Example of Pressure Relief Valve Stability Calculations

Field Changes

Despite all the previous mitigation options, some inadequate relief systems may still require actual field changes. Changes in the field can range from relatively easy and inexpensive to troublesome and exceedingly expensive. Some field changes can include:

- Installation of a bellows conversion kit
- Installation of larger flow area
- Installation of fire-proof insulation
- Modification of relief valve inlet and outlet piping

As mentioned earlier, the batch of pressure relief devices evaluated in the sample study were all lacking adequate documentation as specified in API Standard 521 (Section 4.7). It is important that updated documentation be fully compliant with these documentation requirements.

Conclusions

Based on experience with the overall pressure relief system revalidation project, the sample of relief systems provided a fairly accurate representation regarding the number of inadequacies and types of systematic deficiencies

However, there are several safety issues not identified in the sample study that affect the overall plant, such as low temperature, vibration risk, and the effect of missing data.
As always, there is not a simple solution to all of the safety issues, the experience and expertise of qualified safety professionals must be utilized to identify faults and shortcomings

References:

"Sizing, Selection, and Installation of Pressure Relief Devices in Refineries" 9th Edition, API Standard 520 Part I (2014).

"Sizing, Selection, and Installation of Pressure Relief Devices in Refineries" 6th Edition, API Standard 520 Part II (2015).

"Pressure-relieving and Depressuring Systems" 6th Edition, API Standard 521 (2014).

"Guidelines for Pressure Relief and Effluent Handling", 1st Edition, AIChE/CCPS (1998).

"Maximize the Use of Your Existing Flare Structures", IChemE Hazards XX Symposium, Manchester, United Kingdom (April 2008)