What is My Flare Capacity, *Really*?
Best Practices for Flare QRA Tools

White Paper

Introduction to Flare Quantitative Risk Analysis (QRA)

Most existing pressure relief header and flare systems were originally designed by taking little or no credit for any of the multitude of mitigating measures, commonly referred to as safeguards, which are present in a typical operating facility. However, as plants have increased throughput and added process units, the relief header, and flare systems are usually no longer considered adequate using the same conservative methods that were used in the original design. As such, operating companies are faced with the decision either to install additional relief headers and flare capacity, to bring the system into compliance with the original design methods, or to perform a more detailed engineering analysis, consistent with recognized and generally accepted good engineering practices (RAGAGEP).

It is imperative to distinguish between design or capacity modifications with a real safety benefit and those with a theoretical benefit. Flare QRA (Quantitative Risk Analysis) is a systematic approach to determine the adequacy of a flare system, and this technique can be applied to better understand the risk profile associated with these systems. Flare QRA uses standard statistical analysis and, optionally, Monte Carlo methodology to provide an objective assessment of the risk associated with multiple releases to relief header and flare systems (i.e., “global scenarios”). A QRA can account for the effect of instrumentation, operator intervention, and other layers of protection, as well as the frequency of all relieving scenarios of interest. The Flare QRA method has been utilized by several major operating companies and this method is already included in both the 5th and 6th editions of API STD 521 [1].

Industry Guidance

American Society of Mechanical Engineers Boiler & Pressure Vessel Code (ASME BPVC) Section VIII governs the design of pressure vessels and associated pressure relief requirements but does not give detailed guidance on the design or analysis of relief header and flare systems [2]. For example, ASME Section VIII Appendix M (which is non-mandatory, however, considered to be RAGAGEP) states, “The sizing of any section of common-discharge header downstream from each of the two or more pressure-relieving devices that may reasonably be expected to discharge simultaneously shall be based on the total of their outlet areas, with due allowance for the pressure drop in all downstream sections”. ASME Section VIII does not give details on what constitutes a reasonable scenario and, therefore, leaves this decision up to the judgment of the designer.

API STD 520 and API STD 521 are the most commonly followed industry practices for the design of relief header and flare systems in oil, gas, and chemical facilities [1][3]. Of these two documents, API STD 521 provides the majority of the guidance on the evaluation of overpressure scenarios and the design of relief header and flare systems. API STD 521 provides clear guidance on the selection and analysis of overpressure scenarios for individual process equipment. A list of typical overpressure scenarios that should be considered is presented in API STD 521 along with clear guidance not to consider the positive response of instrumentation when evaluating relief protection for an individual piece of equipment. However, in the design of the relief header and flare systems, the guidance is considerably less clear. Per API STD 521 §4.2.6 and §5.3.43, credit should typically not be taken for favorable instrumentation response when sizing relief devices and disposal system with respect to individual equipment overpressure scenarios. However, such credit may be taken for sizing disposal systems such as flare headers, etc. with respect to global overpressure scenarios. The type, design, reliability, and availability of each safeguard, as well as the effects of each safeguard on the associated flare load must be evaluated carefully. In addition, credit for operator intervention may also be taken to reduce flare loads from specific systems when certain criteria are met. Although the above guidance is certainly not prescriptive, it is apparent that consideration of existing safeguards in the design of the relief header and flare systems may be acceptable.

In addition, there are resources available from industry groups, such as the Center for Chemical Process Safety (CCPS), to explain how users can make better decisions about QRA [4] [5].

Reasons for Performing Flare QRA

Flare QRA is a detailed engineering analysis, and as such, takes considerable time and must be performed by a relief systems engineer with specialized knowledge. It is also important to understand when it is worthwhile to apply the detailed QRA technique to a system. Flare studies that are good candidates to consider evaluating further with this technique usually meet one of the below criteria:

- When baseline relief header and flare evaluation (completed per 29 § CFR 1910.119) identifies significant issues; typically, first-pass flare hydraulics are performed without taking credit for any safeguards [6]. If there are backpressure concerns or in some cases, network equipment calculation concerns, Flare QRA can be performed before making any major changes to the existing flare header;
- To help design the flare header system when contemplating future changes which would increase the relief load to the flare system, such as tying atmospheric relief valves into the existing flare header; or,
- When interested in evaluating the impact of flare maintenance or debottlenecking projects on the flare header.

Establishing Risk Analysis Criteria and Parameters

Data Necessary to Perform Flare QRA

Flare QRA is typically performed after issues are identified in the baseline study, or after tying in additional relief valves into existing the flare header; therefore, relief device loads, and flare header and relief device outlet piping isometrics are generally available. Piping & Instrumentation Diagrams (P&IDs) for the participating equipment and units, and vessel and relief device information are also typically available. In addition, the following information is required:

- Initiating event frequency of global scenarios
- Risk acceptance criteria
- Potential safeguards to mitigate the loads
- Probability of failure on demand (PFOD) for those safeguards

It is important to gain agreement on these parameters before beginning the study, to avoid challenges of the study results and rework. These parameters are discussed in more detail in the sections below.

Initiating Event Frequency

Assessment of the expected frequency of the initiating event (total power failure as an example) must first be established. For facilities that have been in operation for some time, operating history can be used to aid in estimating the expected frequency of various types of failures or initiating events. For example, total power failure may be assumed to occur once every 10 years. If historical data is not available, published reliability data or existing reliability models (such as for the electrical power distribution) can be used to estimate a reasonable conservative frequency for each initiating event. The Center for Chemical Process Safety (CCPS) provides published reliability data for various equipment and instrumentation in the book, "Guidelines for Process Equipment Reliability Data", and the OREDA Participants have published similar data in "OREDA Handbook 2015" [8] [9].

Risk Acceptance Criteria (RAC)

Similar to a Risk Matrix, the Flare QRA Risk Acceptance Criteria (RAC) takes the form of a relationship between vessel accumulation and frequency of occurrence. The RAC defines what the acceptable risk is and how frequently a vessel can exceed a particular accumulation limit. (Note that this does not account for contents or the capacity of any vessel, in determining risk). The vessel accumulation is the percentage over the maximum allowable working pressure (MAWP) that the pressure in the vessel reaches during a relieving event, while the frequency is typically reported as an allowable interval between occurrences, such as once per 100 years. The vessel accumulation is indicative of the potential severity of the aconsequence of the event in terms of loss of containment. Table 1 lists accumulation levels of significance based on standard ASME Section VIII vessel design [2]:

Table 1. Vessel Accumulation vs Severity of Consequence

Accumulation	Significance	Potential Consequence
10%	ASME code allowable accumulation for process upset cases (non-fire) protected by a single relief device.	No expected consequence at this accumulation level. Lowest consequence from qualitative risk matrix.
16%	ASME code allowable accumulation for process upset cases (non-fire) protected by multiple relief devices.	No expected consequence at this accumulation level. Lowest consequence from qualitative risk matrix.
21%	ASME code allowable accumulation for external fire relief cases regardless of the number of relief devices	No expected consequence at this accumulation level. Lowest consequence from qualitative risk matrix.
30%	ASME standard hydrotest pressure for newer designs	Catastrophic vessel rupture not expected at this accumulation level. Possible leaks in associated instrumentation, etc. Medium consequence from qualitative risk matrix.
50%	ASME standard hydrotest pressure	Catastrophic vessel rupture not expected at this accumulation level. Possible leaks in associated instrumentation, etc. Medium consequence from qualitative risk matrix.
~90%	Minimum yield strength (dependent on the materials of construction)	Catastrophic vessel rupture remotely possible. Significant leaks probable. High consequence from qualititative risk matrix.
~300%	Ultimate tensile strength (dependent on the materials of construction)	Catastrophic vessel rupture predicted. Highest consequence from qualitative risk matrix.

Using a facility's Risk Matrix is a good way to develop RAC, as a potential consequence in this table can be linked to a severity level in the risk matrix. For example, if the accumulation in a vessel exceeds the hydrotest pressure once every 10 years, and if the target interval for exceeding hydrotest pressure is less than 1 event in 10 years, then the vessel would not meet the RAC. Acceptable frequencies should be defined for various levels of the variable of interest. RAC must be finalized before running a QRA. Based on Table 1, RAC could be established by assigning the tolerable interval for each level of accumulation; example vessel RAC are presented in Table 2, along with definitions of the criteria.

Table 2. Example Individual Vessel Risk Acceptance Criteria

Accumulation	Tolerable Interval	Notes
0%	Once or more per year	Any number of occurrences is acceptable
21%	Once every 10 years	Consistent with "several occurrences in the facility lifetime"
50%	Once every 50 years	Consistent with "one occurrence in the facility lifetime"
90%	Once every 1000 years	Consistent with "not allowed to occur in the facility lifetime"
110%	No credible occurrences	Most conservative

<u>Individual Vessel Accumulation Frequency Criteria</u>

The purpose of these criteria is to assure that no single vessel is subjected to unacceptable accumulation too frequently. All vessels connected to the Flare Header are evaluated against these criteria regardless of whether relief from the vessel is expected. In order for the system to be deemed acceptable, all vessels in the system should meet these criteria.

For simplicity, these criteria are typically specified uniformly for all equipment, without consideration for contents or capacity. However, as an actual consequence may vary, depending upon a number of factors, it may be appropriate to adjust the criteria for certain systems to align with corporate risk guidelines or applicable regulations.

<u>Virtual System Accumulation Criteria</u>

The purpose of these criteria is to assure that the overall system does not reach unacceptable accumulation too frequently. Unlike the Individual Vessel Accumulation Criteria, the Virtual Vessel Accumulation Criteria approach tracks only the single highest resulting vessel accumulation for each simulation run. It is called a "virtual" vessel approach because the highest accumulation tracked for each simulation run could occur on different vessels or equipment within the system. That is, the accumulation versus frequency performance is not for any single vessel but for the entire system – or a "virtual" vessel in the system. This measure does not indicate how many other vessels could be overpressured. These criteria are approximately one order of magnitude less than those used for individual vessels since the flare system could involve hundreds of vessels. The virtual vessel should meet all Accumulation Criteria for the system to be deemed acceptable.

<u>Average System Accumulation</u>

The purpose of these criteria is to assure that the average of all vessel accumulation is not excessive. This approach is different from the virtual vessel approach in that it keeps track of all vessel accumulations that result from each simulation. Because it keeps track of all vessel accumulations and frequencies, the results can be converted to an "average" vessel. For example, a 100% average accumulation once every 1000 years would mean that one vessel (any vessel) in the system would reach 100% accumulation every 1000 years. These criteria are identical to the virtual vessel criteria and approximately one order of magnitude less than those used for individual vessels. The "average" vessel should meet all Accumulation Criteria in order for the system to be deemed acceptable.

Safeguards and Probability of Failure on Demand (PFOD)

The QRA engineer identifies potential safeguards that currently exist that could mitigate an individual vessel's relief load to flare in the event of a global scenario. The safeguards which can reduce or eliminate relieving events can typically be identified by analyzing the P&IDs and reviewing each system with operating personnel. The list below highlights some typical safeguards that are present in most operating facilities and often aid in reducing or eliminating relieving loads:

- Operator intervention in field
- Operator intervention from control room
- Basic process control system (BPCS)
- Spare pump auto-starts
- Independent high-pressure shutdowns
- Independent high or low liquid level shutdowns
- Independent high-temperature shutdowns

- Specific pump or system operation time
- Safety instrumented system (SIS)

Each safeguard is assigned a probability of failure on demand which indicates the safeguard's reliability. Mitigated relief loads are calculated for each vessel that has the benefit of safeguards.

Examples of typical safeguards and associated PFODs are given in Table 3.

Table 3. Typical Safeguards and Associated PFODs

Safeguard	PFOD, percent
Conventional instrumentation	10 – 20%
High pressure / high temperature override	5%
Spare pump autostart	10%
Operator field intervention	30 – 80%
SIL-1	1 – 10%
SIL-2	0.1 – 1%
SIL-3	0.01 – 0.1%
Mode of operation	Varies based on usage

The presence of safeguards leads to high possible variance in the total global scenario relief load when that global scenario actually occurs. For example, consider the equipment in Figure 1, consisting of 10 vessels which relieve during a global scenario. Assuming each has 1 layers of protection, which either function or fail to function, there may be as many as two different possible relief rates for each vessel; therefore, each global scenario in this example could have 1,024 different global flare load permutations (210). Ignoring the safeguards would mean that the flare analysis would be based on the most conservative case, out of more than a million permutations. Flare QRA allows for the analysis of the flare system to be based on thousands, if not all, of the possible permutations.

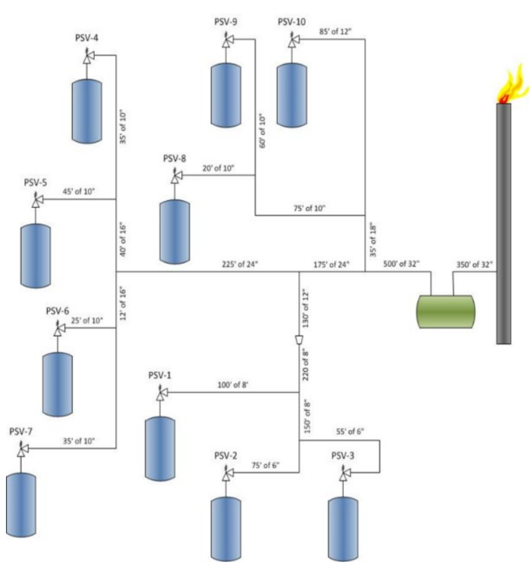

Figure 1. Example Relief Header Network

Performing the Flare QRA

Calculation of System Risk Profile

With the data collected in the above steps, the relationship between vessel accumulation and frequency of occurrence for the system can be calculated for comparison to the established RAC. This is accomplished by generating all possible permutations of safeguards, calculating the probability of each of these permutations, analyzing the relief header pressure profile for each permutation, and calculating the vessel accumulations from the backpressure obtained from the pressure profile. Table 4 shows an example of the type of data stored for each permutation, for the flare system in Figure 1. Note that the vessel accumulations at the locations which do not relieve are set equal to zero, as the pressures in the vessels are not expected to reach the MAWP due to the operation of the relevant safeguards.

Table 4. Global Scenario Example – Sample Run Data

Relief Device	Vessel	Safeguard Operates?	Probability	Relief Rate (lb/hr)	Vessel Accumulation
PSV-001	V-001	No	10%	110,000	36%
PSV-002	V-002	No	10%	90,000	54%
PSV-003	V-003	Yes	90%	0	0%
PSV-004	V-004	No	10%	225,000	25%
PSV-005	V-005	No	10%	350,000	67%
PSV-006	V-006	Yes	90%	0	0%
PSV-007	V-007	Yes	90%	0	0%
PSV-008	V-008	No	10%	215,000	38%
PSV-009	V-009	No	10%	230,000	16%
PSV-010	V-010	Yes	90%	0	0%
Total				1,220,000	

Accumulation

The vessel accumulations in Table 4 were calculated based on flare header backpressure. The vessel accumulation analysis needs to consider the specific relief device type (e.g., conventional, bellow, pilot-operated). Two simplifying assumptions are made. First, the relief rate is treated as a function of safeguard activity only, and not vessel accumulation. While it is theoretically possible to eliminate this assumption and utilize a relief rate vs. accumulation matrix, doing so would exponentially increase the complexity of an already computationally intensive simulation. Second, the pressure in the relieving systems would be increased such that each relief device maintains full lift at the hydraulically determined backpressure.

Several complications and considerations follow from these assumptions.

- While it may not be practical to adjust individual relief rates based on accumulated pressures, it is a straightforward exercise to determine the maximum possible accumulated pressure (i.e., the internal pressure at which there would be no theoretical relief rate) for each system. This value can then be utilized as an upper bound in the evaluation.

- Below certain backpressure limits, balanced bellows relief valves may require less differential pressure to maintain full lift than conventional relief valves. Above these limits, however, the bellows can be expected to fail. It should be determined prior to starting calculations how to account for backpressure exceeding bellows limits. Typical bellows rating limits can be obtained from API Standard 526, though manufacturers may have published values for their valves [7].
- If the disposal system includes pilot-operated relief devices which are not expected to relieve under the scenario under evaluation, it should be noted that excessive backpressure may result in the opening of these devices and lead to backflow as discussed in API STD 520 Part II [3]. Many modern pilot-operated valves include backflow preventers, but the potential for backflow, leading to potential system accumulation where none was expected, should be considered.

What Results Can Be Expected from a Flare QRA

Assuming the safeguards are independent, the overall probability for this particular permutation is equal to the product of the respective individual probabilities for each safeguard corresponding to the stated load from each vessel (in the above example from Table 4), or 6.56x10-7. The results can then be sorted per the accumulation ranges in the RAC; see Table 5.

Table 5. Global Scenario Example – Overall Probability per Single Safeguard Permutation

Relief Device	Vessel	Accumulation Exceeds 21%	Accumulation Exceeds 50%	Accumulation Exceeds 90%
PSV-001	V-001	$6.56x10^{-7}$	0	0
PSV-002	V-002	$6.56x10^{-7}$	$6.56x10^{-7}$	0
PSV-003	V-003	Yes	0	0
PSV-004	V-004	$6.56x10^{-7}$	0	0
PSV-005	V-005	$6.56x10^{-7}$	$6.56x10^{-7}$	0
PSV-006	V-006	Yes	0	0
PSV-007	V-007	Yes	0	0
PSV-008	V-008	$6.56x10^{-7}$	0	0
PSV-009	V-009	No	0	0
PSV-010	V-010	Yes	0	0

The probability of exceeding a given level of accumulation from the RAC can then be computed for all possible permutations by first summing the respective overall probability for each safeguard permutation. Then the frequency of occurrence for the initiating event (total power failure) should be factored, i.e. once per 10 years or 0.1 occurrences per year. As such, the frequency at which the vessel exceeds that level of accumulation is estimated. The reciprocal of the frequency yields the interval of occurrence in terms of years between occurrences. The overall results from the entire analysis are shown below in Table 6.

Table 6. Global Scenario Example – Calculated Risk Profile

Relief Device	Vessel	Accumulation Exceeds 21% (years between occurrences)	Accumulation Exceeds 50% (years between occurrences)	Accumulation Exceeds 90% (years between occurrences)
	RAC	**10**	**50**	**1000**
PSV-001	V-001	100	10,000	Never
PSV-002	V-002	100	526	Never
PSV-003	V-003	100	100	10,000
PSV-004	V-004	948	Never	Never
PSV-005	V-005	361	1,000	8,074,283
PSV-006	V-006	11,137	148,528	$1x10^{10}$
PSV-007	V-007	36,340	36,340	$3.6x10^{9}$
PSV-008	V-008	100	3,835	$1.886x10^{8}$
PSV-009	V-009	484	90,690	Never
PSV-010	V-010	100	Never	Never

Consequence Modeling

If desired, these permutations may now be analyzed with dispersion models to describe how the material is dispersed downwind. If the release involves flammable materials, fire and explosion models are used to convert the information determined from the source models into energy hazard potentials (e.g., thermal radiation, explosion overpressure) [4] [10].

Challenges

Challenge 1 – Considering Only Individual Equipment May Skew the View of the Resulting Risk

Individual Vessel Accumulation Criteria are readily understood, whereas the Virtual System and Average System Criteria are comparably abstract concepts. This can lead to an inappropriate bias focused only on Individual Vessel Accumulation Criteria and occasionally the failure to adopt System Level Criteria. This would be a significant error. The Individual Vessel Accumulation Criteria evaluates the risk to each source in isolation, giving little explicit information on how stressed the disposal system is as a system. This data is provided by the System Level Criteria.

As an example of the Virtual System Criteria, see Table 7 below, which shows the maximum predicted accumulation levels for five equipment, with each occurring during a different global scenario:

Table 7. Virtual System Example

Relief Device	Vessel	Scenario	Accumulation Exceeds 50% (years between occurrences)
	RAC		**50**
PSV-011	V-011	Scenario 1	200
PSV-021	V-021	Scenario 2	250
PSV-031	V-031	Scenario 3	150
PSV-041	V-041	Scenario 4	225
PSV-051	V-051	Scenario 5	200
Virtual System			**40**

V-031 shows the highest risk of any individual vessel with a predicted accumulation exceeding 50% once every 150 years, or a 0.67% chance each year, a value which is only one-third the maximum accepted probability. Based on the Virtual Vessel Criteria, however, it is observed that the probability of some vessel exceeding 50% accumulation is once every 40 years, or a 2.5% chance each year. Clearly stated, the disposal system has a 2.5% chance of reaching excessive pressure any given year, which provides a better data point for assessing the adequacy of the disposal system than would be obtained from the Individual Vessel Accumulation Criteria alone.

For Average System Criteria, using input from Table 6 above, the probabilities of accumulation can be summed at each level for all equipment, giving the results in Table 8:

Table 8. Average System Example

	Accumulation Exceeds 21% (years between occurrences)	Accumulation Exceeds 50% (years between occurrences)	Accumulation Exceeds 90% (years between occurrences)
Average System	18	75	9,987

Accordingly, on 'average', a vessel is predicted to exceed 21% accumulation once every 18 years, or a 5.6% chance each year. A vessel is also predicted to exceed 50% accumulation once every 75 years, or a 1.3% chance each year. Again, this Average System Criteria provides a better measure of the overall disposal system adequacy than the Individual Vessel Criteria alone.

Challenge 2 – How System-Level Risk is Defined

Recognizing the interpretive challenge posed by the System Level Criteria to non-relief specialists, additional methodologies can be utilized to assess overall performance. In particular, header pressures can be tracked at specific points of interest. As with probabilities of accumulation levels in the RAC, the probabilities of reaching certain pressure levels at these points can be reported and are seen in Table 9:

Table 9. Pressure Tracking

Pressure Tracking Node	Header Location	5 psig (years between occurrences)	10 psig (years between occurrences)	20 psig (years between occurrences)
001	KO Drum D001	10	10	50
002	KO Drum D002	10	10	50
003	Unit 001 Tie-in	15	60	240
004	Unit 002 Tie-in	10	100	10,000
005	Unit 003 Tie-in	35	1,000	10,000
006	Unit 004 Tie-in	15	30	150

Such approaches can be particularly useful in flare debottlenecking as well as in evaluating locations for new load sources, whether from atmospheric tie-in or expansion projects. Nevertheless, for an accurate representation of risk, the best practice should be to consider these methods as supplemental to, and not replacement for, the System Level Criteria.

Challenge 3 – Not Evaluating All Global Scenarios

It must be stressed that the RAC is defined in terms of total, or overall, risk –not just risk from any one initiating event. As such, it is important to evaluate all potential global scenarios, and not only the worst-case or controlling event(s). Consider Table 10 below, for which Scenario 1 is the known Design Case, resulting in the highest disposal system pressures. By comparison, all other global scenarios are minor and are qualitatively recognized to carry less risk.

Table 10. Cumulative Effect of Evaluating Multiple Scenarios

Vessel	Global Scenario	Accumulation Exceeds 50% (years between occurrences)
RAC		**50**
V-001	Scenario 1 (Design Case)	55
V-001	Scenario 2	750
V-001	Scenario 3	1000
V-001	Scenario 4	800
V-001	*Cumulative*	*46*

Due to the low risk for Scenarios 2, 3, and 4; it could be tempting to short-cut the analysis and only evaluate Scenario 1 – and indeed the qualitative risk assessment would be confirmed. Yet doing so would result in the wrong conclusion, as the calculated 1 in 55-year interval for Scenario 1 exceeds the minimum given 1 in 50-year interval required for risk acceptance. Accounting for the other scenarios, the cumulative interval is 1 in 46 years, which does not meet the criteria.

Challenge 4 – Verification of Reliability Data Used for Flare QRA Input

As with any risk-based analysis, Flare QRA is a probabilistic tool, and uncertainties in available reliability data introduce corresponding uncertainties in the assessment. This reliability data is needed in two areas: (1) the reliability of the systems; be they electrical, steam, cooling water, instrument air, etc. for which a failure can result in a global overpressure scenario; and (2) reliability of the protective systems, or safeguards, for which mitigative credit is being taken.

Typically, this information is taken from facility experience; from published generic reliability data; or vendors. In some cases, such as SIL rated protective equipment, PFOD data may be well known. Electrical distribution systems can be rigorously evaluated based on each component to calculate overall dependability. In all cases, the utilized reliability data should be reasonably conservative. As long as specified initiating event frequencies are not less than actual, and specified safeguard reliabilities are not greater than actual, the Flare QRA methodology will give conservative results.

Nevertheless, variances on both sides can significantly alter the outcome. The frequency of any single event, or permutation, is the product of the frequency of the initiating event and cumulative probability resulting from the action of all safeguards:

$\boldsymbol{F_i} = \boldsymbol{I_i} \prod \boldsymbol{S_i}$, where

$\boldsymbol{F_i}$ is the frequency, in years between occurrences, of a specific load permutation

$\boldsymbol{I_i}$ is the frequency, in years between occurrences, of the initiating event

S_i is the probability of action, or inaction, of each safeguard

For example, say a scenario expected once every 10 years results in relief from two pieces of equipment, both of which have one safeguard of 90% reliability. The result is four possible permutations with the given probabilities, which are given in Table 11:

Table 11. Load Permutations for Two Equipment with One Safeguard Each

	Safeguard Acts			
Equipment A	Yes	Yes	No	No
Equipment B	Yes	No	Yes	No
Probability	81%	9%	9%	1%
Frequency (Years between Occurrences)	12.35	111.11	111.11	1,000

However, if there is a 25% uncertainty in the frequency of the initiating event, the table would instead be (Table 12):

Table 12. Load Permutations with Initiating Event Uncertainty

	Safeguard Acts			
Equipment A	Yes	Yes	No	No
Equipment B	Yes	No	Yes	No
Probability	81%	9%	9%	1%
Frequency (Years between Occurrences)	9.3 – 15.4	83.3 – 139	83.3 – 139	750 – 1,250

If compounded by a 10% uncertainty in the reliability of the safeguard for Equipment A, the results become (Table 13):

Table 13. Load Permutations with Initiating Event Uncertainty and Safeguard Uncertainty

	Safeguard Acts			
Equipment A	Yes	Yes	No	No
Equipment B	Yes	No	Yes	No
Probability	73 – 89%	8 - 10%	1 - 17%	0.1 - 2%
Frequency (Years between Occurrences)	8.4 – 17	76 – 154	44 – 1,389	395 – 12,500

As demonstrated, as the probability for a specific permutation gets lower – which often means the failure of safeguards, and greater consequence – the variance becomes ever greater, and the interval between expected events becomes harder to define. No reliability datapoint will ever be known with 100% accuracy, but it is critical to eliminate as much uncertainty as possible while remaining appropriately conservative.

Issues *Not Directly* Addressed by Flare QRA

With regards to consequence, Flare QRA focuses on the potential for loss of containment resulting from excessive overpressure of equipment during a global scenario. However, flare and disposal systems present other risks that are not explicitly accounted for by the RAC in a Flare QRA, and meeting all RAC does not absolve the responsible party from adequately addressing these other issues using other approaches. While not directly addressing these issues, data resulting from Flare QRA can help in further evaluation.

Flare Tip

Emergency releases resulting from global overpressure scenarios often exceed the original design flow rates for installed flare tips, especially since facilities have steadily expanded and increased throughput over the years. This can lead to increased thermal radiation, and in extreme cases, issues such as flame-out.

Flare QRA data, in the form of expected flare load probabilities, can assist in evaluating these risks. The level of granularity with regards to flare load-interval size can be specified to suit the precision required. Further, as each load interval may represent hundreds, or even thousands, of different permutations, the probability of each permutation can be assessed to determine the most representative run, or set of runs, for each interval, as seen in Table 14:

Table 14. Expected Frequency of Flare Load

Flare Load (lb/hr)	Years Between Occurrences
> 200,000	5
> 300,000	10
> 400,000	30
> 500,000	100
> 600,000	500

Once representative permutations have been identified, further flare tip evaluations – including rigorous radiation and dispersion modeling – can be performed. These results would then be assessed against the applicable risk policies.

Note that further complications may arise if significant variability in relief load composition is possible even within the defined buckets. This challenge may be overcome through a layered approach, wherein the same bucketing methodology is applied to each discrete flare load set based on molecular weight or total load fraction of components of interest.

Knockout Drums

Knockout drums present additional disposal system equipment which may not perform as desired if actual conditions exceed the original design. API STD 521 §5.7.9.6 briefly discusses some considerations for potential knockout drum overfill [1]. Other risks may apply if vapor velocities do not permit adequate residence time to limit liquid drop size, or result in re-entrainment.

While perhaps more challenging, if appropriate consequence models are applied a similar approach as that suggested for Flare

Tips can be utilized to determine a risk profile. At the simplest level, a yearly probability for overfilling a drum can readily be defined.

Acoustic and Flow Induced Vibration

Significant pressure reduction at relief devices and any choke points in the disposal system can generate considerable acoustic energy. In addition to the noise hazard, this can induce vibration within the pipe wall that may lead to fatigue failure, from Acoustic Induced Vibration (AIV). Turbulence within the fluid flow may also lead to piping vibrations, called Flow Induced Vibration (FIV). Methods for calculating the energies inducing these vibrations are available in the literature [11]. API Standard 521 §5.5.12 discusses acoustic fatigue in some detail and provides some mitigative strategies [1].

Global relief scenarios can present an increased AIV and FIV hazard, as the sound power levels (dB) from AIV sources, such as relief devices, are additive and high flow rates increase turbulence. Though consequences must be defined separately, Flare QRA can determine probabilities for significant AIV or FIV threats, aiding the evaluation of further mitigations.

Defining a Design Capacity

In many cases, it is helpful to have a defined design rate or capacity. Under traditional approaches, it will be at this rate that the flare tip, knockout drum, vibration, etc. criteria discussed above are evaluated. The design rate is also utilized when evaluating the disposal system impact of projects of various kinds.

A full Flare QRA, in which all possible load permutations are assessed and weighted based on probabilities does not terminate in the production of a design rate. Further, rerunning the Flare QRA analysis may not be practical for every change or 'what-if' analysis. However, explicit information is given on load probabilities and provided there is buy-in from all stakeholders good engineering judgment can be applied to identify an appropriate rate or rates, to use for these purposes.

Conclusion

Quantitative risk analysis can be applied to evaluate complex relief header and flare systems. Consistent with current industry practices, credit can be taken for safeguards to mitigate relief loads to the header system. By considering availability for each safeguard and the initiating event frequency, a relationship between the predicted vessel accumulations and overall frequency of occurrence can be developed to represent the risk profile for each individual vessel and the overall system. In a manner similar to the qualitative risk evaluation process used at many facilities, the calculated risk profile can be compared to corporate risk acceptance criteria.

There are challenges and limitations when performing QRA, including how the system level risk is defined, verification of reliability data used as QRA inputs, and identifying a flare system design capacity. A thorough understanding of QRA inputs, the scope of the QRA, the risk acceptance criteria, and the different accumulation criteria is necessary before performing the analysis.

The Flare QRA methodology can serve as a practical approach to resolve a previously intractable problem and may allow operating companies to better understand and manage the risk associated with relief header and flare systems.

References

[1] American Petroleum Institute, API Standard 521 "Pressure-relieving and Depressuring Systems," 6th edition, 2014.

[2] American Society of Mechanical Engineers, ASME Boiler and Pressure Vessel Code, Section VIII, Div.1 "Rules for Construction of Pressure Vessels," 2017 Edition.

[3] American Petroleum Institute, API Standard 520 "Sizing, Selection, and Installation of Pressure-Relieving Devices," Part I, 9th Edition (2014) and Part II, 6th Edition (2015)

[4] Center for Chemical Process Safety, "Guidelines for Chemical Process Quantitative Risk Analysis," 2nd ed., John Wiley and Sons (2000).

[5] Health & Safety Executive, Research Report RR25 "Application of QRA in Operational Safety Issues," (2002).

[6] U.S. Occupational Safety and Health Administration, 29 CFR § 1910.119 Process Safety Management of Highly Hazardous Chemicals, 1994.

[7] American Petroleum Institute, API Standard 526 "Flanged Steel Pressure-relief Devices," 7th edition, 2018.

[8] Center for Chemical Process Safety, "Guidelines for Process Equipment Reliability Data, with Data Tables," John Wiley and Sons (1989).

[9] SINTEF (Stiftelsen for industriell og teknisk forskning), Offshore and Onshore Reliability Database, OREDA 2015 Handbook, 6th Edition, 2015.

[10] N. Prophet, "Understand Your Vulnerabilities with Quantitative Risk Analysis," Chemical Engineering Progress, pp. 49-52, July 2016.

[11] F. Eisinger, R. Sullivan, P. Feenstra, D. Weaver, "Acoustic Vibration in a Stack Induced by Pipe Bends," Proceedings of the 5th International Symposium on FSI, AE, &FIV, at 2002 ASME Int'l Mechanical Engineering Congress and Exposition.

Acronyms

AIV	Acoustic Induced Vibration
BPCS	Basic Process Control System
FIV	Flow Induced Vibration
MAWP	Maximum Allowable Working Pressure
P&ID	Piping and Instrumentation Diagram
PFOD	Probability of Failure on Demand
RAC	Risk Acceptance Criteria
RAGAGEP	Recognized and Generally Accepted Good Engineering Practice
QRA	Quantitative Risk Analysis
SIS	Safety Instrumented System

Published by

Siemens Process & Safety Consulting
15375 Memorial Drive
Houston, TX 77079, USA

For more information, please visit our website:
siemens-energy.com/process-safety