Second Annual Symposium, Mary Kay O'Connor Process Safety Center
"Beyond Regulatory Compliance: Making Safety Second Nature"
Reed Arena, Texas A&M University, College Station, Texas
October 30-31, 2001

Quantitative Risk Analysis – A Realistic Approach to Relief Header and Flare System Design

John T. Perez
Berwanger, Inc.
4615 Southwest Frwy, Suite 925
Houston TX 77027

Phone: (713) 570-2967

ABSTRACT

As process industry facilities increase production capacity and add processing units, existing relief headers and flare systems are frequently found to no longer meet the same conservative design criteria used for the original design of the facility. This presentation will show how Quantitative Risk Analysis (QRA) may be used to develop a more detailed understanding of the safety issues associated with the design of such systems. Examples will be presented in which QRA has resulted in large cost savings by revealing that proposed multi-million dollar relief header and flare system modifications would have resulted in insignificant reductions in a facility's risk to personnel safety.

Most existing pressure relief headers and flare systems were originally designed with little or no consideration of the probabilities or consequences of specific design scenarios, and without taking credit for the operation of the multitude of safeguards present in a typical operating facility that would have a mitigating effect on these probabilities and consequences. The primary reason for this conservative approach was the lack of sophisticated tools and reliability data required to analyze the relationships among initiating events, event probabilities, safeguard reliabilities, and consequences. However, recent advances in modeling techniques, in the collection of reliability data, and in the availability of computing power have now rendered these complex relationships tractable and have made QRA a practical tool for relief header and flare system analysis.

The traditional methods for performing relief header and flare system design made no effort to distinguish among initiating events based on their anticipated frequency. Relatively common events, such as a compressor failure (expected to occur perhaps once per year) were treated in the same manner as such rare events as total electric power failure (expected to occur perhaps once in the facility's lifetime).

On the other hand, with the QRA approach presented here, a higher level of a consequence (for example, pressure relief valve back pressure) may be deemed acceptable for the power failure event, due to its low frequency of occurrence. By differentiating events based on anticipated probability, the relief header system may not be required to be designed to the same criteria for each initiating event. In addition, this approach allows a more accurate assessment of the aggregate risk for the relief header system as the frequency/consequence relationship for the sum of all the initiating events can be defined.

QRA also allows the inclusion of the impact of safeguards - such as shutdowns, conventional instrumentation, and operator intervention - on the likely consequences of an initiating event. Although the assumption that no safeguards are present is reasonable when evaluating the pressure relief for an individual piece of equipment, it becomes more unnecessarily conservative as the number of safeguards involved in the event increases. For example, the probability of failure on demand (PFOD) of a single shutdown valve on a reboiler's steam supply line may be 10%. Certainly, this is frequent enough to require the installation of a relief device to provide overpressure protection to the individual reboiler and its associated distillation equipment. However, when a flare system is designed to handle the relief device effluent from ten such distillation systems, the simultaneous PFOD for all ten steam shutdown valves is 0.110 or once every ten trillion demands. The author – as well as the management of many operating companies – would assert that this is not frequent enough to justify significant expenditure on relief header or flare system upgrades. In this relatively simple example of a single safeguard on each of ten distillation systems, there are 210, or 1,024 possible outcomes. This presentation will show how the QRA process can be used to define more clearly the probability/severity relationship of the many possible outcomes of significantly more complex process facilities.

The inclusion of the initiating event frequency and safeguard reliability yields a frequency versus outcome relationship for variables of interest to flare system design - such as system hydraulics, flare tip design capacity, flare radiation levels, and knockout drum performance. A review of this relationship versus corporate risk tolerance criteria can be used as an

Quantitative Risk Analysis – A Realistic Approach to Relief Header and Flare System Design

John T. Perez
Berwanger, Inc.
(713) 570-2967 Tel
(713) 570-2999 Fax
www.berwanger.com

Introduction

Most existing pressure relief header and flare systems were originally designed taking little or no credit for any of the multitude of mitigating measures, commonly referred to as safeguards, present in a typical operating facility. However, as plants have increased throughput and added process units, the relief header and flare systems are no longer adequate given the same conservative methods that were used in the original design. As such, operating companies are faced with the decision of installing additional relief header and flare capacity to bring the system into compliance with the original design methods or evaluating the relief header and flare capacity using more realistic design methods. To further complicate this decision, past experience during flaring events often contradicts the theoretical calculations that indicate the system is undersized.

Limited budgets have rendered it imperative to distinguish between additions and modifications with a real safety benefit and those with a theoretical benefit. With this in mind, a more realistic approach to the analysis of pressure relief header and flare systems that is consistent with recognized and generally accepted good engineering practices (RAGAGEP) is required. Quantitative risk analysis (QRA) can be applied to the problem to better understand the risk profile associated with these systems. The application of QRA renders it possible to evaluate the relief header and flare system accounting for all safeguards as well as the frequency of all the relieving scenarios of interest. The QRA method presented has been utilized by several major operating companies and is proposed for inclusion in the next revision of API RP 521.

Industry Guidance

ASME 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. For example, ASME VIII Appendix M (non-mandatory) 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 VIII does not give further details on the determination of what constitutes a reasonable scenario and, therefore, leaves this decision up to the judgment of the designer.

API RP 520 and API RP 521 are the most commonly followed industry practices for the design of relief header and flare systems in oil, gas, and chemical facilities. Of these two documents, API RP 521 provides the majority of the guidance on the evaluation of overpressure scenarios and the design of relief header and flare systems. API RP 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 Table 2 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. API RP 521 Section 2.2 states, "Fail-safe devices, automatic start-up equipment, and other conventional control instrumentation should not replace pressure-relieving devices as protection for individual process equipment. However, in the design of some components of the blowdown header, flare, and flare tip, favorable instrument response of some percentage of the instrument systems can be assumed. The percentage of instrument response is generally calculated based on the amount of redundancy, maintenance schedules, and other factors that affect instrument reliability." In addition, API RP 521 Section 5.2.1 states that, "Consideration may also be given to the capability for and timing of operator intervention as a means of reducing system loads." Although the above guidance is certainly not prescriptive, it is apparent that inclusion of existing safeguards in the design of the relief header and flare systems is acceptable.

Current Design Methods

The primary goal in the design of a relief header system is to ensure that the developed back pressures in the system do not adversely impact the relief devices to an extent that the MAWP plus allowable accumulation for the associated equipment is exceeded. In order to accomplish this goal, the designer must identify all credible scenarios that are expected to result in a significant release to the relief header and flare system. Typical scenarios that are considered include facility-wide power failure, partial power failure, cooling water failure, instrument air failure, steam failure, and external fire. For each of these global scenarios, a relief load must be assigned to each relief device that is expected to discharge due to overpressure of the associated equipment. Typically, these relief loads were already developed when the relief devices and associated vessel nozzle sizes were specified, so these loads are also used as the basis for the global overpressure scenarios. As noted above, the relief loads used to size individual relief devices are developed assuming no positive response from any existing safeguards; therefore, a list of relief loads is prepared for each global scenario based on no positive response from any of the available safeguards.

Once the relief loads for each global scenario have been established, a model of the relief headers from each relieving device to the ultimate discharge location, such as the flare tip, is developed. This will typically be accomplished using one of several commercially available software packages that are designed specifically for the hydraulic analysis of relief header networks. Based on a set of relief loads entering the network and a known pressure at the outlet or outlets from the network, the pressure profile throughout the relief header network is established. Of particular interest is the back pressure at the flowing relief devices as back pressure can reduce the capacity of a relief device or change the pressure at which the device operates, either of which may result in higher than expected pressure accumulation in the protected equipment. API RP 520 and relief device manufacturers provide guidance on the impact of back pressure on the opening pressure and capacity of various types of relief devices. As such, a review of the calculated back pressures and relief device types is performed to ensure that the adequate relief capacity is available at the appropriate pressure.

Certainly, if the relief header and flare system is analyzed assuming no positive response from any safeguards and found to be adequate, the system satisfies the most conservative design criteria and further analysis is not warranted. However, as is most commonly the case in existing facilities, if the above analysis identifies inadequacies in the system, then further steps are required. The most common solutions in recent years have been to either add high integrity pressure protection systems (HIPPS) to reduce or eliminate the largest relief loads to the system or to install additional relief header capacity. Given the difficulty and expense associated with routing additional relief headers, HIPPS have become the preferred solution for many operating companies.

HIPPS are independent of the basic process control system and are designed to be significantly more reliable than that conventional instrumentation. The complication that ultimately arises is how reliable the HIPPS must be in order to ensure that it will reduce or eliminate the associated relief load as planned. This problem is further complicated when multiple HIPPS are installed and the discussion of how many HIPPS can be relied upon enters the decision making process. In the case of multiple HIPPS, a common assumption is that the HIPPS associated with the largest relief load fails to operate, while the remaining HIPPS operate as planned. The underlying assumption is that the probability of two HIPPS failing simultaneously is so remote that the scenario need not be considered regardless of consequence.

While engineering judgment can be applied in cases where only a few safeguards are considered, the accuracy of such judgment decreases as the number of safeguards increases. For example, the probability of failure on demand (PFOD) of a single shutdown valve on a reboiler steam supply line may be 10%. Certainly, this is too frequent to eliminate the presence of a relief device to provide overpressure protection for one particular column; however, when the flare system design is performed, there may be 10 such columns in which case the simultaneous PFOD for all 10 steam shutdown valves is 0.1^{10} or once every 10 billion demands. On the other hand, the probability of all the steam shutdown valves working correctly is 0.9^{10} or a reliability of approximately 35%. In between these two extremes are the other 1,022 possible permutations that could occur (total number of permutations is $2^{10} = 1,024$).

Historically, the evaluation of the pressure profile for a single case was a difficult and time-consuming task that had to be repeated for each identified global scenario. Hand calculations even for simple piping networks were very time consuming. With the advent of computer routines, software packages became available that could efficiently provide more rigorous analysis of relief header systems. However, the typical software package is still set up to handle a single case at a time. The user sets up the relief header network, inputs the relief loads and conditions for each case being considered, and then stores the file as a single case. As such, the analysis of any significant number of permutations becomes extremely time-consuming, not to mention the difficulties associated with analyzing data from many individual case files. A tool is required that will automate the analysis of the relief header network for many cases and store the results to facilitate analysis.

Right Tool for the Job

Tools are now available to allow the automated analysis of many different permutations for a relief header network. As discussed above, a system with ten safeguards will have 1,024 possible outcomes depending on which safeguards function appropriately. By establishing the loads and safeguards at each of the ten relief sources the generation of the various outcomes can be automated resulting in 1,024 different permutations of relief loads to the relief header system. Then by automating the analysis of the relief header network solution module, each one of these cases can be analyzed, and the back pressure results stored in database format. Furthermore, based on the PFOD of the safeguards, the probability of each of the 1,024 permutations can be directly calculated. The end result is a relationship between the back pressure at each relief device and the associated probability of occurrence. In terms of risk, the vessel accumulation that is calculated from the simulated back pressure on the associated relief device represents the consequence, and the calculated probabilities represent the likelihood. While this relationship provides significantly more insight into the system than simply selecting one case for analysis based on engineering judgment, the process can be taken further to better define the risk associated with the identified relieving scenarios.

Risk Analysis

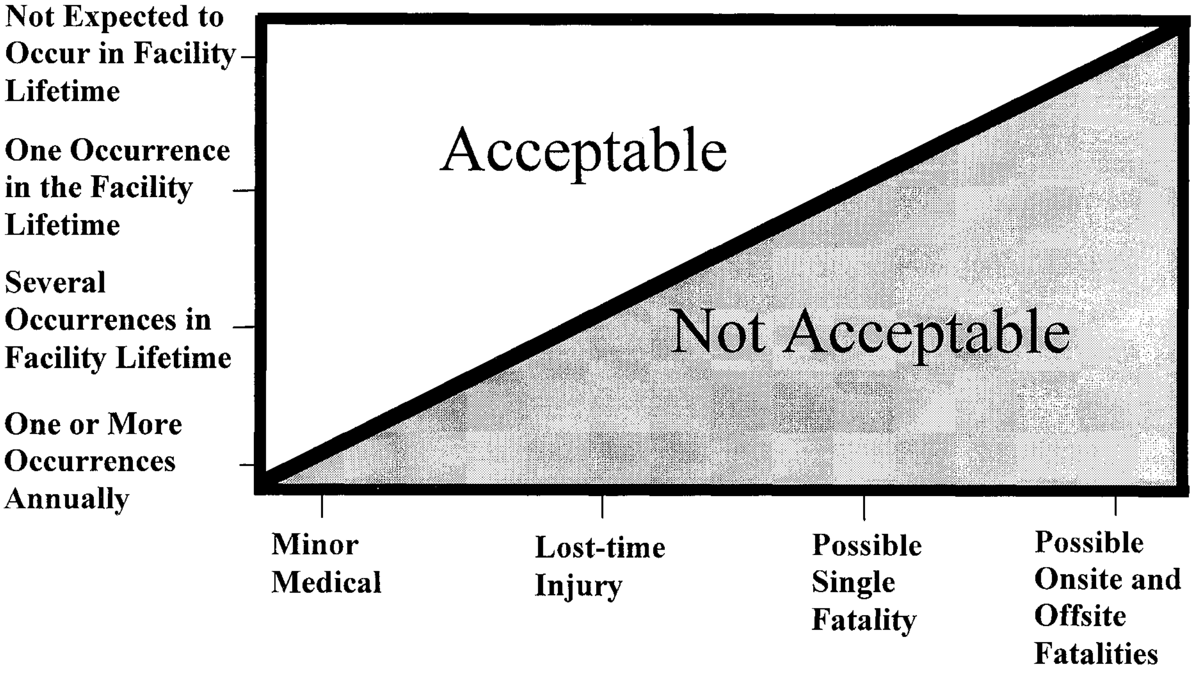
Prior to discussing the application of QRA to the relief header system problem presented above, it is worthwhile to examine how companies currently deal with safety issues as a whole. The primary means currently utilized by operating companies to prioritize and resolve safety issues is qualitative risk assessment. As implied by the term qualitative, the process is primarily left to the judgment of plant personnel. For example, the typical PHA process identifies potential safety issues that are then qualitatively risk-ranked based on perceived consequence and likelihood. A typical risk matrix is shown below:

Figure 1 – Qualitative Risk Matrix

Likelihood/Consequence	Minor medical treatment	Lost-time injury	Possible single fatality	Possible fatalities onsite and offsite
One or more occurrences annually	3	4	5	5
Several occurrences in the facility lifetime	2	3	4	5
One occurrence in the facility lifetime	1	2	3	4
Not expected to occur in the facility lifetime	1	1	2	3

As the matrix shows, the higher the number, the higher the perceived risk for the particular safety concerns. The high risk items (4 and 5) will generally require immediate mitigation; the medium risk items (3) often can be mitigated at the next scheduled maintenance interval; and the low risk items (1 and 2) may not require mitigation or may be mitigated using procedures or training. As such, the risk associated with the low risk items (1 and 2) is usually deemed to be tolerable. The tabular information can then be recast in graphical format.

Figure 2 – Qualitative Risk Acceptance Criteria



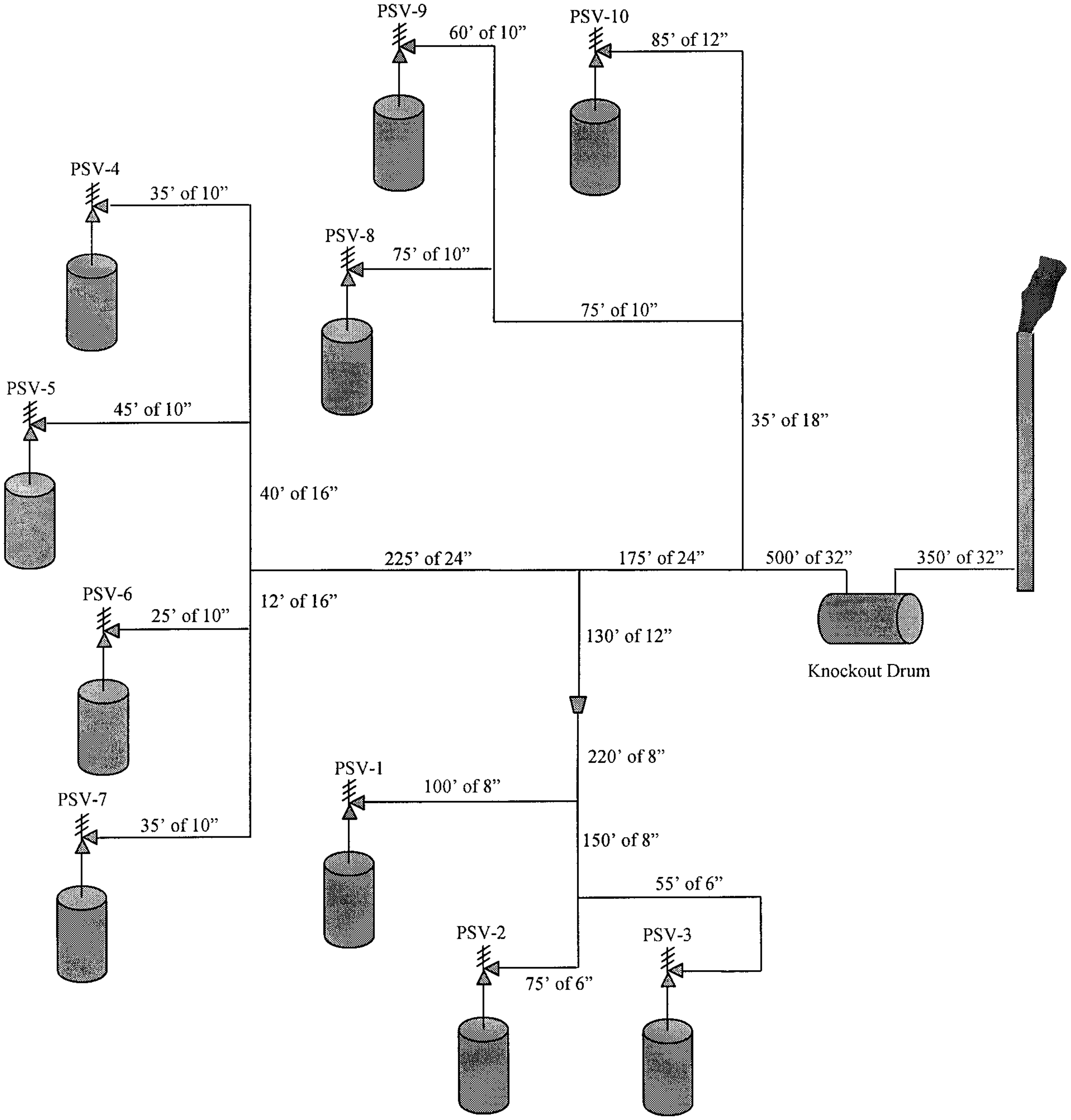
The dividing line between acceptable and not acceptable is the point at which the risk level changes from 2 to 3. The application of quantitative risk analysis (QRA) to relief header systems is based on precisely the same principle with the addition of numeric results to aid in the assessment of the risk.

Similar to the qualitative approach summarized above, the end goal of the quantitative risk analysis is the development of a relationship between likelihood and consequence. The likelihood can be determined by calculating the frequency of occurrence for a particular scenario. Applying this concept to relief header and flare systems requires that the frequency of occurrence of the initiating event under consideration (i.e. total power failure occurs once every 10 years) be estimated along with the probability of a particular outcome (i.e. probability calculated from individual safeguard PFODs). The consequence of a particular outcome can be assessed based on the predicted pressure accumulation in the equipment. The hydraulic analysis of the relief header model yields the pressure profile throughout the relief header. From the back pressure at the outlet of each relief device, the vessel accumulation can be calculated based on the type of relief device. For example, a conventional relief valve opens on differential pressure. Therefore, if the relief valve is set at 100 psig and the calculated back pressure is 50 psig, then the pressure in the vessel, assuming that relief is required, would be 150 psig plus the additional overpressure, typically 10%, required to achieve full opening of the relief valve or 160 psig. This pressure accumulation provides a measure of the consequence, as it is apparent that the higher the accumulation the more potential there is for a loss of containment.

Quantitative Risk Analysis of Relief Headers – Example

The following relief header network with 10 vessels involved in a total power failure scenario will be used as a simple example to demonstrate the concepts described above. The relief header network and associated pipe sizes and equivalent lengths are shown in Figure 3.

Figure 3 – Total Power Failure Example – Relief Header Network



The QRA process can be divided into the following steps:

- Analysis of worst-case
- Development of risk acceptance criteria (RAC)
- Identification of initiating event frequency
- Identification of safeguards and associated probability of failure on demand (PFOD)
- Calculation of system risk profile
- Analysis of results

Analysis of Worst-case

Prior to embarking into a more rigorous analysis, an evaluation of the baseline worst-case should be performed. In general, this is done by establishing the relief loads associated with each initiating event assuming no credit for positive instrument response from any of the available safeguards and then evaluating the relief header system pressure profile. The back pressures at the relief devices are then compared to relief device specific limits to determine acceptability. In the event that the back pressures at all of the devices are acceptable, no further analysis is required. However, if back pressures are found to exceed accepted limits, the remaining steps can be taken to assess the risk associated with the system. As stated in the introduction, many facilities find that increases in throughput and additional tie-ins to the relief header have rendered the system unacceptable assuming no credit for instrument response.

Table 1 summarizes the inputs and results for the worst-case evaluation of the system shown in Figure 3.

Table 1 – Total Power Failure Example – Worst-case Hydraulics Summary

Relief Device	Relief Valve Type	Vessel	MAWP/Set Pressure (psig)	Relief Load (lb/hr)	Back Pressure (psig)	Predicted Vessel Accumulation (% over MAWP)
PSV-001	Conventional	V-001	250	110,000	113	55%
PSV-002	Conventional	V-002	160	90,000	124	88%
PSV-003	Conventional	V-003	140	150,000	125	100%
PSV-004	Conventional	V-004	325	225,000	68	31%
PSV-005	Bellows	V-005	50	350,000	65	110%
PSV-006	Bellows	V-006	50	45,000	58	96%
PSV-007	Bellows	V-007	50	85,000	59	97%
PSV-008	Bellows	V-008	50	215,000	62	104%
PSV-009	Bellows	V-009	60	230,000	59	77%
PSV-010	Conventional	V-010	250	465,000	65	36%
Total				1,965,000		

Clearly from the results in Table 1, the predicted vessel accumulations are in excess of code allowable limits; therefore, a further analysis of the safeguards that are present to reduce relief loads to the header system is warranted. The worst-case results also bound the high end of the vessel accumulations that must be considered in the risk acceptance criteria as discussed below.

Development of Risk Acceptance Criteria (RAC)

The risk acceptance criteria (RAC) takes the form of a vessel accumulation versus frequency relationship. 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 interval between occurrences, such as once per 100 years. The vessel accumulation is taken to be a measure of the potential consequence of the event that primarily would be a loss of containment of some magnitude. The following accumulation levels are of significance based on standard ASME VIII vessel design:

Table 2 – Vessel Accumulation Versus Consequence Relationship

Accumulation (% over MAWP)	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 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.
50%	ASME standard hydrotest pressure (may be 30% on new designs)	No catastrophic vessel rupture expected at this accumulation level. Possible leaks in associated instrumentation, etc. Medium consequence from qualitative risk matrix.
~90%	Minimum yield strength (dependent on materials of construction)	Catastrophic vessel rupture remote possibility. Significant leaks probable. High consequence from qualitative risk matrix.
~300%	Ultimate tensile strength (dependent on materials of construction)	Catastrophic vessel rupture predicted. Highest consequence from qualitative risk matrix.

From Table 2, a numerical RAC can be developed from the qualitative risk matrix by assigning reasonable intervals to the qualitative frequency categories.

Table 3 – Individual Vessel Risk Acceptance Criteria

Accumulation (% over MAWP) Exceeds	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 1,000 years	Consistent with "not expected to occur in the facility lifetime"
110%	No occurrences	Based on the worst-case, the maximum accumulation for any of the vessels in the system is 110%

Identification of Initiating Event Frequency

As an assessment of the frequency is required to utilize the above RAC, the frequency of the initiating event (total power failure in the example case) must first be established. In this way, the frequency of the different failures that affect the relief header and flare systems can be taken into account. For facilities that have been in operation for some time, past operating history can be used to aid in identifying the expected frequency of various failure modes. If historical data is not available, published reliability data or existing reliability models (typically for the electrical power distribution) can be used to estimate failure frequencies. From these sources, a reasonable, conservative frequency can be established for each initiating event. For the example, a total power failure will be assumed to occur once every 10 years.

Identification of Safeguards and Associated Probability of Failure on Demand (PFOD)

The safeguards present to reduce or eliminate relieving events can typically be identified by analyzing the Piping and Instrumentation Diagrams (P&ID) and reviewing each system with operations 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

- Spare Pump Auto-Starts
- Independent High Pressure Shutdowns
- Independent High or Low Liquid Level Shutdowns
- Independent High Temperature Shutdowns
- High Integrity Shutdowns (SIL-I, SIL-II, and SIL-III)

In the example, the probability of failure on demand (PFOD) for each of the safeguards will be set to 10% for simplicity. In actuality, this value is established based on a rigorous review of the available safeguards for the system of interest along with historical operating data and published reliability data. 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 the 3rd of Edition of "Offshore Reliability Data." For more complex control schemes, application of fault tree analysis may be required to assess the reliability of a particular safeguard.

Once the reliability of the various safeguards is established, the outcome if the safeguard operates needs to be established. Typically, the safeguard will serve to completely eliminate the relief situation, such as in the case of a steam supply valve on a reboiler that is closed by a high pressure shutdown. However, in some cases the relief load may only be reduced, such as in the case of a fired heater that has a high pressure shutdown on the fuel gas. In this case if flow through the heater continues, some residual heat input can be expected, and the relief situation may not be completely avoided. For the example, it is assumed that with the exception of V-009, all of the safeguards serve to completely eliminate the relief load when appropriate function is realized. Table 4 summarizes the two possible outcomes at each relief location along with the assumed 10% PFOD for each safeguard.

Table 4 – Total Power Failure Example – Summary of Safeguards

Relief Device	Vessel	MAWP/Set Pressure (psig)	Relief Load (lb/hr)	Safeguard PFOD	Reduced Relief Load (lb/hr)
PSV-001	V-001	250	110,000	10%	0
PSV-002	V-002	160	90,000	10%	0
PSV-003	V-003	140	150,000	10%	0
PSV-004	V-004	325	225,000	10%	0
PSV-005	V-005	50	350,000	10%	0
PSV-006	V-006	50	45,000	10%	0
PSV-007	V-007	50	85,000	10%	0
PSV-008	V-008	50	215,000	10%	0
PSV-009	V-009	60	230,000	10%	50,000
PSV-010	V-010	250	465,000	10%	0
Total			1,965,000		50,000

The total relief load to the system will be 1,965,000 lb/hr assuming all of the safeguards fail and only 50,000 lb/hr if all of the safeguards work appropriately. The other various possible combinations will fall somewhere between these two extremes in terms of severity.

Calculation of System Risk Profile

With the input data collected in the above steps, the vessel accumulation versus frequency relationship for the system can be calculated for comparison to the established RAC. This is accomplished by generating each possible permutation 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 back pressures obtained from the pressure profile. By storing the results for each case in a database the accumulation versus frequency relationship is established for each vessel. Table 5 summarizes the type of data that is stored for each case (one of the 1,024 possible permutations). Note that the vessel accumulations at the locations that do not relieve as a result of the appropriate function of the identified safeguard are set equal to zero as the pressures in the vessels are not expected to reach the MAWP due to operation of the relevant safeguards.

Table 5 – Total Power Failure Example – Sample Run Data

Relief Device	Vessel	MAWP/Set Pressure (psig)	Safeguard Operates?	Probability	Relief Load (lb/hr)	Back Pressure (psig)	Vessel Accum.
PSV-001	V-001	250	No	10%	110,000	65	36%
PSV-002	V-002	160	No	10%	90,000	71	54%
PSV-003	V-003	140	Yes	90%	0	63	0%
PSV-004	V-004	325	No	10%	225,000	49	25%
PSV-005	V-005	50	No	10%	350,000	43	67%
PSV-006	V-006	50	Yes	90%	0	32	0%
PSV-007	V-007	50	Yes	90%	0	32	0%
PSV-008	V-008	50	No	10%	215,000	29	38%
PSV-009	V-009	60	No	10%	230,000	22	16%
PSV-010	V-010	250	Yes	90%	0	19	0%

Analysis of Results

Assuming the safeguards are independent, the probability of this particular case is equal to the product of the probabilities of the outcomes at each vessel or 6.56×10^{-7} in this case. The results can then be stored in bins that are consistent with the accumulation ranges in the RAC as shown in Table 6.

Table 6 – Total Power Failure Example – Run Data Storage

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	0	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	0	0	0
PSV-007	V-007	0	0	0
PSV-008	V-008	$6.56x10^{-7}$	0	0
PSV-009	V-009	0	0	0
PSV-010	V-010	0	0	0

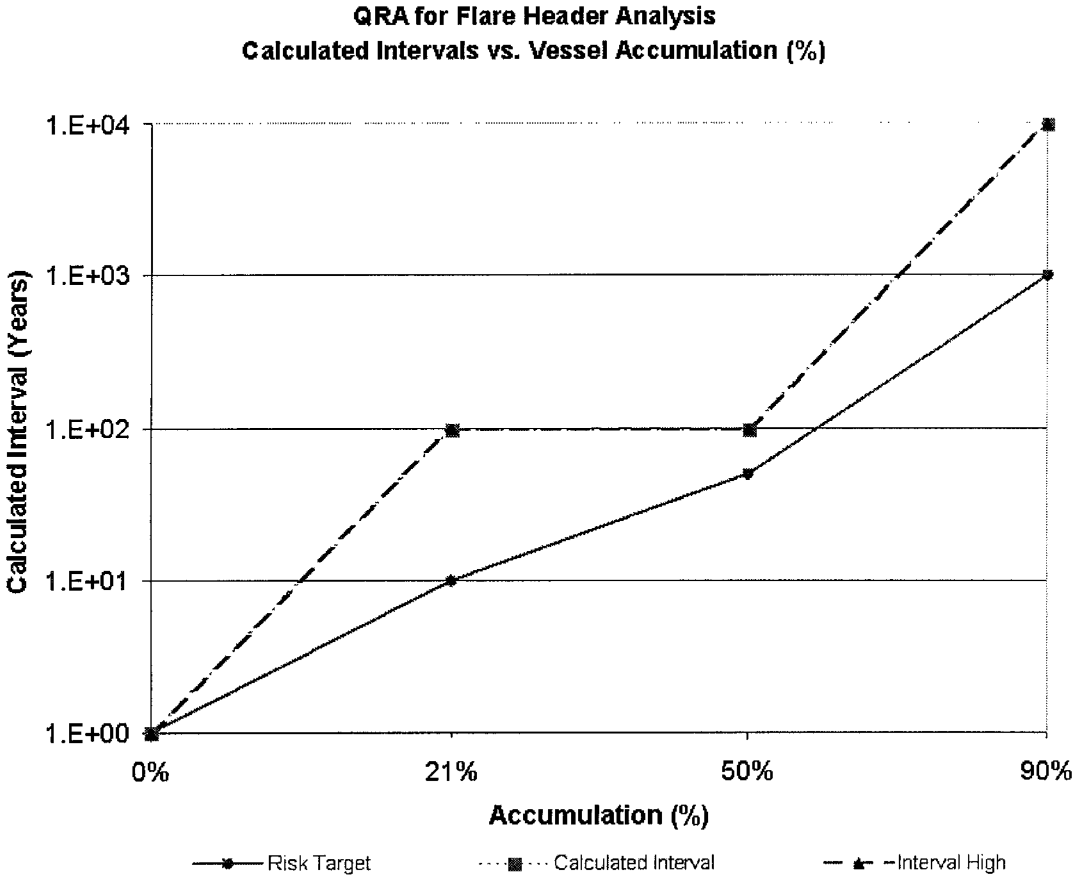
The probability of exceeding a given level of accumulation from the RAC can then be computed for all possible permutations by summing the probabilities from each run. To restate, this yields the probability of exceeding a particular level of accumulation in the event that a total power failure were to occur. The final piece of the equation to develop the frequency versus accumulation relationship is the frequency of occurrence for the initiating event (total power failure) that was established as once per 10 years or 0.1 occurrences per year. By multiplying the occurrences per year by the probability for each vessel exceeding a particular level of overpressure the frequency at which the vessel exceeds that level of overpressure is defined. The reciprocal of the frequency yields the interval of occurrence or, to restate, the years between occurrences. The results from the entire analysis are shown below.

Table 7 – Total Power Failure 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***	***1,000***
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	3,411	36,340	$3.6x10^{9}$
PSV-008	V-008	100	3,835	$1.88x10^{8}$
PSV-009	V-009	484	90,690	Never
PSV-010	V-010	100	Never	Never

As Table 7 shows, all of the vessels involved in the total power failure meet the established RAC. For each vessel, the information can be compared to the RAC graphically by plotting the calculated risk profile as compared to the RAC as shown below for V-003.

Figure 4 – Total Power Failure Example – Calculated Risk Profile Versus RAC



The graphical representation shows that the calculated interval of occurrence for each level of accumulation is greater (less frequent) than the tolerable interval specified in the RAC; therefore, the relief header and flare system is found to be adequate after accounting for the safeguards that are available and the expected frequency of the initiating event.

Other Considerations

Monte Carlo Techniques

One of the key considerations in applying this technique to larger relief header and flare systems is the feasibility of analyzing all of the possible permutations of safeguards. In the example above, the total number of permutations for a single initiating event is 1,024. For facility-wide relief header and flare systems, the total number of safeguards and the total number of initiating events can be significantly higher. For example, had the total number of safeguards been 15 and the number of initiating events considered been 3, then the total number of permutations requiring analysis would have been 2^{15} for each of the three initiating events or 98,304. The large number of permutations combined with increased time required to solve the relief header model can render the time required to perform the analysis impractical. In this case, Monte Carlo techniques can be used to achieve a result to a specified accuracy without running each individual permutation.

Monte Carlo analysis involves the generation of a specified number of random runs of the system. To summarize, a random number is generated for each location that has an associated safeguard to determine if the safeguard functions or not. For example, with a PFOD of 10%, a random number between 0 and 0.1 would predict a failure, while a random number between 0.1 and 1.0 would predict appropriate operation of the safeguard. By executing this process at each location that has a safeguard, a random simulation of the initiating event is generated. The relief header model is then executed, and the results stored in a similar fashion as described above. As more random simulations are executed, the certainty in the results increases. Statistical methods can be used to determine the number of required random simulations to reach a suitable confidence level in the results. In general, the number of simulations required is impacted by the intervals set in the RAC. As each simulation represents a number of years of facility operation equal to the interval of occurrence for the initiating event (total power failure every 10 years in the above example), it makes sense that more simulations would be required to accurately represent a once every 10,000 year event versus a once every 100 year event. To summarize, Monte Carlo techniques can render the required computations practical when the number of total permutations requiring analysis becomes unwieldy.

Aggregate Risk

The above example looked at the risk profile for each individual piece of equipment. A more global evaluation of the risk can be performed by looking at the aggregate risk for the system. The aggregate risk is a function of the individual vessel risk profiles and the total number of vessels involved in the analysis. The quantification of the aggregate risk provides a measure of how often any of the vessels attached to the relief header and flare system could be expected to exceed a given accumulation. As Table 8 shows below, the aggregate risk is assessed by summing the frequencies (reciprocal of intervals from Table 7) for all the vessels. The system frequency can then be converted back to a cumulative interval by taking the reciprocal of the system frequency.

Table 8 – Total Power Failure Example – Calculated Aggregate Risk Profile

Relief Device	Vessel	Accumulation Exceeds 21% (Events/Year)	Accumulation Exceeds 50% (Events/Year)	Accumulation Exceeds 90% (Events/Year)
PSV-001	V-001	0.01	0.0001	Never
PSV-002	V-002	0.01	0.001901	Never
PSV-003	V-003	0.01	0.01	0.0001
PSV-004	V-004	0.001055	Never	Never
PSV-005	V-005	0.00277	0.001	1.24E-07
PSV-006	V-006	8.98E-05	6.73E-06	Never
PSV-007	V-007	0.000293	2.75E-05	2.78E-10
PSV-008	V-008	0.01	0.000261	5.32E-09
PSV-009	V-009	0.002066	1.1E-05	Never
PSV-010	V-010	0.01	Never	Never
System	Frequency	0.056274	0.013307	0.0001
Cumulative	Interval	17.8 yr	75.1 yr	9,987 yr

Table 8 shows that one vessel (any one of the ten) attached to the relief header and flare system could be expected to exceed 21% accumulation every 17.8 years. A separate RAC can be established for the system as a whole for comparison to the calculated aggregate risk profile.

Reducing Risk

In addition to providing a tool to evaluate the risk associated with existing or proposed relief header and flare systems, QRA can be used to identify the most cost-effective remedies to the system in the event that risk acceptance criteria are not met. Typical remedies include:

- Altering the relief device type (i.e. converting conventional relief valves to bellows or pilot-operated relief valves)
- Providing additional safeguards
- Upgrading the reliability of existing safeguards
- Physical modifications to the relief header and flare system

The most common remedy is the addition of more safeguards or upgrading the reliability of existing safeguards. QRA provides a tool to determine which safeguards will have the most impact on the system risk profile ensuring that each addition or upgrade is performed at the optimal location. The same concept applies to physical modifications to the relief header system. QRA will identify the areas of the relief header and flare system that have the highest exposure; therefore, allowing the identification of bottlenecks in the system. As such the optimal locations for increasing header pipe sizes or adding parallel headers can be identified.

Conclusion

With the advent of more powerful computer modeling tools, quantitative risk analysis can be applied to the analysis of complex relief header and flare systems. Consistent with current industry practices, credit can be taken for safeguards that will serve to mitigate relief loads to the header system. By establishing reliabilities for each safeguard and the frequency of the initiating event being considered, 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 to determine the acceptability of the system. Furthermore, in the event the system is found unacceptable, QRA provides a tool to identify the most cost-effective solutions to any identified system inadequacies. The QRA methodology presented above provides an analytical solution to a previously intractable problem and allows operating companies to better understand and manage the risk associated with relief header and flare systems.