MAXIMISE THE USE OF YOUR EXISTING FLARE STRUCTURES

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INTRODUCTION

Due to the design vintage of many petroleum refineries and petrochemical plants, existing pressure relief and flare systems may be overloaded because of:

- Prior unit expansions/upgrades which have increased the load on the flare for combined flaring scenarios beyond the original design intentions
- The desire to connect atmospheric relief valves to the flare for environmental and safety consideration and to eliminate blow down drums
- The addition of new process units that need access to flaring capacity

As a result, many petrochemical and chemical companies are engaged in comprehensive flare systems evaluation and upgrading projects to ensure continuing safe operations, to maximise the use of their existing flare systems, and to minimise the need for modifying existing flare structures or building new ones.

Achieving these goals presents several engineering challenges:

1. Which existing atmospheric relief devices present vapor cloud explosion and thermal radiation hazards and need to go to the flare?
2. What is the impact of the additional flaring loads on the existing flare header system and individual relief devices during combined flaring events (such as loss of power or cooling)?
3. Where and how many High Integrity Protection Systems (HIPS) should be employed to reduce the worst-case flaring load?
4. How should the HIPS components be configured to achieve the required safety integrity level (SIL)?

In order to properly and cost-effectively address these design questions, specialized expertise and tools for pressure relief systems design, risk analysis, and instrumentation are required:

- Dynamic simulation of relieving vessels and flare piping networks to identify capacity constraints
- Risk tolerability criteria related to vessel overpressure hazards
- Risk assessment and reliability analysis to properly select and configure the HIPS

This paper provides a general framework for evaluating and maximizing available flare systems capacity, and investigates criteria and approaches for determining a tolerable risk event for flare systems.

HIPS, SIS AND SILS: WHAT ARE THEY?

The ISA/ANSI Standard S84.01 96 defines a Safety Instrumented System (SIS) as a system composed of sensors, logic solvers, and final control elements for the purpose of taking the process to a safe state when predetermined conditions are violated. SISs act independent of the basic process control system (BPCS).

The term high integrity protective system is described in Annex E of API STD 521 Guide to Pressure-Relieving and Depressuring Systems, as an alternative in some scenarios for preventing overpressure conditions. A HIPS is a SIS that is designed to provide overpressure and over-temperature protection that is at least equivalent in reliability to a mechanical relief device.

HIPS have traditionally been used for rapid depressurization of Hydrocrackers and Acetylene Hydrogenators in runaway conditions, to simultaneously reduce pressure and remove heat, where a safety valve is ineffective. More recently, HIPS have been employed to remove the heating supply to fractionation columns to avoid activation of the pressure relief device and causing a release to atmosphere or a flare system. In this use it is a secondary overpressure protective system for the purpose of optimizing the design of the flare header system and connected pressure devices.

The Safety Integrity Level (SIL) is the discrete integrity level (SIL 1, SIL 2, SIL 3) of the SIS defined in terms of Probability of Failure on Demand (PFD) as presented in Table 1.

FLARE SYSTEM ANALYSIS

ESTABLISH GLOBAL OVERPRESSURE SCENARIOS

The first step is to establish worst-case global overpressure scenarios. Typically these are caused by failure of a utility system such as electric power (partial or total) or cooling water. Other typical potential causes are instrument air failure or fire. The global fire flaring load is often determined by applying a 232 m^2 (2500 ft^2) fire circle based on API STD 521 (7.1.2), but does not usually define the worst case flaring load event.

Table 1. Safety integrity level

Safety integrity level	Probability of failure on demand average range (PFDavg)
1	10^{-1} to 10^{-2}
2	10^{-2} to 10^{-3}
3	10^{-3} to 10^{-4}

When developing global scenarios, consideration of basic process control systems (BPCS) and safeguards is also necessary to establish a credible event. For example credit can be given for some failure positions of control valves per API STD 521 (7.1.4.3). Credits or debits for other properly designed safeguarding systems may also be appropriate.

This review should conclude with an inventory of all the individual flare loads pertaining to each global scenario including relief devices, control valves, depressuring valves, etc. This will allow the establishment of a design flare load base case.

VERIFY RELIEF DEVICE CAPACITY

To complete the global scenario assessment, flow capacity information for different relief device contingencies is required. Depending on plant age and quality of relief systems documentation, this information may be incomplete or lacking for existing facilities. In most cases, it becomes necessary to verify the relief loads based on material and energy balance information and valve mechanical data. Other aspects that need to be considered when verifying the flows include:

- Multi-component representation of stream compositions
- Device inlet and outlet piping configuration
- Relief device flow and opening characteristics for accurate representation of peak flow
- The presence of multiphase, supercritical, high-viscosity, and/or reacting flows

CONSTRUCT FLARE NETWORKS MODEL

To cost-effectively analyze the flare system hydraulics requires constructing a network model of the flare collection system. This involves characterizing the geometric layout of the flare main header and sub-headers, including appropriate dimensional aspects. The individual design case flare loads are tied into the headers at their respective locations.

ANALYZE FLARE SYSTEMS HYDRAULICS

The flare network model is exercised to obtain a base-case flare system profile which establishes:

- Backpressure, flow reduction, pressure accumulation (%MAWP), and temperature accumulation (%MAWT) for protected equipment
- Sub-header, main header, and flare tip flow restrictions
- Exclusion zones for thermal radiation and noise restrictions

This base-case profile is used to identify sub-headers and individual relief devices that are deficient.

Many of these deficiencies are often associated with relief device instability caused by excessive inlet pressure loss or backpressure. Shelly (1999), confirms our experience that 30 to 40% of pressure relief valves in existence violate recommended guidelines for inlet pressure loss and backpressure. Excessive pressure loss can lead to valve instability and possibly valve failure. As a result, many operating companies are faced with significant upgrade or mitigation costs.

Typical flare system design and operating constraints are shown in Tables 2A and 2B. These design and operating constraints can differ depending on where the facility is located and who the operator/owner is.

At this point, an evaluation of options to correct the deficiencies is undertaken, with the purpose of maximizing the use of the existing flare collection system. Options that are usually considered include:

- Automate shutdowns and/or isolation systems currently requiring operator intervention
- Maximum use of bellows/pilot relief valves
- Account for actual timing of loads (e.g., automated de-pressuring systems)
- Make reasonable header and relief piping size adjustments to correct deficiencies, if possible
- Model vessel dynamics and establish actual pressure and temperature accumulation based on flare pressure profiles when using (a) reduced set points less than MAWP, and where (b) the required flow rate is less than the actual relief device rated capacity.

These aspects need to be thoroughly investigated and evaluated before consideration of HIPS as an alternative option. Flare systems mitigation can be costly. Careful analysis and

Table 2A. Typical flare system hydraulics design and operating constraints

Design criteria	Value	Description
Maximum Flow Velocity	Mach ≤ 0.6	Maximum value for header and sub-headers design
Flow rate	Rated Capacity	Value for sub-headers and relief discharge piping design
	Required Capacity	Value for main header design
Backpressure	$\leq 0.1\ P_{set}$	Conventional relief valves
	$\leq 0.3\ P_{set}$	Balanced relief valves. Balanced relief valves may be accepted for backpressures up to 0.5 P_{set} with prior consultation with manufacturer and ioMosaic Corporation
	$\leq 0.5\ P_{set}$	Pilot operated valves. Pilot relief valves will be accepted for backpressures up to 0.7 P_{set} with prior consultation with manufacturer and ioMosaic Corporation

Table 2B. Typical flare system thermal radiation and noise design and operating constraints

Design criteria	Value		Description
Radiation Intensity	1.57 kW/m^2	500 BTU/h ft^2	Value at any location where personnel with appropriate clothing may be continuously exposed
Solar radiation component should be added and can be as high as 1 kW/m^2 in some locations	1.98 kW/m^2	630 BTU/h ft^2	Maximum value for pressured storage equipment
	3.15 kW/m^2	1000 BTU/h ft^2	Maximum value for atmospheric storage equipment
	4.72 kW/m^2	1500 BTU/h ft^2	Heat intensity in areas where emergency actions lasting several minutes may be required by personnel without shielding but with appropriate clothing. Maximum value for Process equipment.
	6.30 kW/m^2	2000 BTU/h ft^2	Heat intensity in areas where emergency actions up to 1 minute may be required by personnel without shielding but with appropriate clothing. Maximum value for Knock Out Drum.
	9.45 kW/m^2	3000 BTU/h ft^2	Heat intensity at any location to which people have access; exposure should be limited to a few seconds, sufficient for escape only.
Emergency Flaring Noise (working areas)	85 dBA		At maximum flaring load
Emergency Flaring Noise (residential areas)	80 dBA		At maximum flaring load
Normal operation Flaring Noise (residential areas)	68 dBA		At maximum flaring load

use of accurate and detailed simulation tools will ensure continued safety and a cost effective mitigation implementation where required. SuperChems™ Expert, or other flare network modeling software, can be used to produce more accurate answers for flow dynamics and flare sub-header optimization. This is crucial for effective selection of mitigation options where necessary.

HIPS EVALUATION

Typically HIPS are considered for de-bottlenecking existing flare collection systems in order to address one or more of the following conditions, without having to significantly modify the existing flare structures or building new ones:

- Header and/or sub-header connection Mach Number > 0.6
- Excessive relief device backpressure
- Excessive vessel accumulation/overpressure
- High flare thermal radiation levels on/off site
- High flare noise levels on/off site
- Adding atmospheric relief devices to the existing flare collection system

SELECT HIPS CANDIDATES

HIPS are generally applied to vessels that require external heat input, such as a distillation column. HIPS can also be applied to reactor vessels where crash cooling or isolation of feed may be required to prevent a runaway reaction. Quickly isolating the source of heat eliminates emergency venting for certain global scenarios. For petroleum refineries, HIPS are used on columns to eliminate power or cooling failure flare loads. The potential candidates are actually a result of the base design case global scenarios determination. Some potential candidates may be eliminated on the basis of a relatively small load that doesn't justify the cost of installing a HIPS system.

DEFINE HIPS CONFIGURATIONS

This activity focuses first on addressing the sub-header deficiencies. Using the base-case load information, a preliminary selection of HIPS equipment and identification of safety integrity levels (SILs) is established. This involves a risk-based analysis to determine the number of HIPS and the SILs required, and requires the establishment of a tolerable overpressure event risk criteria, which will be discussed later. These criteria are used to fix a tolerable event frequency target which is then utilized to evaluate different HIPS failure sequences to arrive at a possible design case.

CONFIRM HIPS DESIGN FLARE LOADS

A HIPS failure sequence and resulting flare loads that meet the target event frequency is run through the network simulation model to obtain new values for backpressure, accumulation, flow rates, Mach number and radiation/noise profiles from the flare. Depending on the results, HIPS configuration will be refined by adjusting the number of HIPS and SILs, and the simulations repeated. Several iterations may be performed to arrive at a cost-effective and tolerable risk solution.

VERIFY REQUIRED SIL

Once the HIPS design configuration is finalized, the next task is to analyze the proposed HIPS design to verify that the specified components and arrangement will meet the safety integrity level (SIL) requirement, which will be discussed later in this paper.

RISK CONCEPTS APPLIED TO FLARE SYSTEM DESIGN

DEFINE TOLERABILITY CRITERIA

A flare system which exerts excessive backpressure on relief devices poses a hazard to pressure vessels depending on the degree of overpressure. The risk tolerability of an overpressure condition in a vessel should be assigned based on:

- The consequences (effect) of the overpressure in terms of vessel integrity
- The frequency at which the severity of the overpressure can be tolerated

Effects of pressure accumulation on steel vessels designed to ASME VIII pressure vessel code are well documented and presented in Table 3. A set of risk criteria can be established using these overpressure effect characteristics.

In devising the criteria, one begins by deciding what level of overpressure is not acceptable and assigning a very low event frequency such as 1 in a million years (10^{-6}/yr). The probability of vessel failure becomes significant for any overpressure event that subjects a vessel to a pressure of 300% of the MAWP. No one should knowingly design for such an event. Hence, accumulations greater than this value are not considered. When setting the frequency for the 165–300% accumulation event, a value of 10^{-5}/yr is selected, which is an order of magnitude less than the unacceptable value for pressure accumulations

Table 3. Effect of pressure accumulation in carbon steel vessels

Accumulation (%)	Effects	Remarks
<135	None expected	None
135–165	Potential for slight permanent deformation	This range of pressure corresponds to the tensile limit of the vessel, and is both material- and code-dependent. The lower and upper limits correspond to ASME VII, Div. 2, and ASME VIII, Div. 1 (1998 edition and earlier) vessels, respectively. ASME VIII, Div. 1 (1998 edition with 1999 addenda) vessels fall in between these values. Therefore a representative value for this range is 150%.
165–300	Permanent deformation, possible small leak	Valid for remote contingencies, as more frequent overpressuring could weaken the vessel by fatigue
300–400	Same as above, but with a higher likelihood of a large leak or burst	Dangerous overpressuring
400–500	Burst	Typical for healthy ASME VIII code vessels

Table 4. Pressure accumulation frequency

Accumulation (%)	Frequency
<135	1 in 100 years (10^{-2}/yr)
135–165	1 in 1000 years (10^{-3}/yr)
165–200	1 in 10,000 years (10^{-4}/yr)
200–300	1 in 100,000 years (10^{-5}/yr)
>300	Not allowed

of greater than 300%. However, this pressure range spans a level that is barely above hydro-test at one extreme to a level above the yield point at the other. While a frequency of 10^{-5}/yr seems right for the upper end of the range, it is quite conservative at the lower end.

A better risk-consequence characterization is obtained by further dividing the 165 to 300 range into two ranges: 165–200 and 200–300; with frequencies of 10^{-4}/yr and 10^{-5}/yr respectively.

SELECT TARGET EVENT FREQUENCY

The target frequency for an overpressure event is determined from the matrix shown in Table 4 using the calculated vessel accumulations from the base-case network simulation. The process begins with analysis of each sub-header and associated loads. The HIPS candidate with the worst accumulation is used to establish the target frequency. Reducing flare loads in the sub-headers is often sufficient for achieving a satisfactory overall flare system design.

Combined scenarios involving HIPS failures on any device connected to the flare may need to be examined to complete the design. For example, failures occurring within the total HIPS population are considered when evaluating the radiation or noise effects from a global scenario. Also, the tolerable frequency target may be more relaxed for the radiation event than overpressure.

DETERMINE SAFETY INTEGRITY LEVEL

For each recommended HIPS, a design specification needs to be developed that details the actual configuration for the vessel being protected. The specified components and redundancy must be able to achieve the SIL requirement determined from the risk-based HIPS selection process. The application of fault tree analysis is an accepted method for determining the expected availability of a SIS or HIPS.

REFINE AND IMPROVE EQUIVALENT SIL BASED ON FUNCTIONAL TEST INTERVAL

The application of fault tree analysis has been shown effective in establishing the relative frequency of potential incidents associated with base-case and alternative HIPS design configurations. The technique has the versatility to handle equipment and control failures along with human errors. Examples of the application of fault tree and reliability analysis for evaluation of safety interlock systems have been reported elsewhere.

Since ISA is a performance based standard, it sets reliability performance requirements, rather than different integrity levels for an interlock based on configuration such as:

Type 3: Fully redundant components
Type 2: Partially redundant components
Type 1: No component redundancy

However, it may be possible to achieve a required SIL with lower reliability hardware through reduction of the test interval (i.e., more frequent testing).

Using appropriate component failure rates, the fractional dead times presented in Table 5 were calculated with incorporation of common cause failure. As Table 5 illustrates, this provides the decision-maker with a good picture of the reliability trade-offs for a given mission (testing interval) duration.

This information can also be utilized for determining reliability (availability) for different SIS configurations (e.g., Type 1 – fully redundant). For example, these data were used to determine the interlock reliability (1 – fractional dead time) for the three types of level interlock configurations as a function of functional testing interval (Table 6).

The reliability values account for common cause failures. Without considering common cause failures, the Type 3 system would meet SIL 3 criteria with monthly and quarterly testing. Analyzing the sources of common cause unreliability and if possible reducing its impact is also worth investigation before making a final select of SIS configuration.

As seen in Table 6, there is a trade-off between testing frequency, and the advantage gained by selecting the next higher SIL configuration. Combining these results with the

Table 5. Unreliability of level interlock systems with consideration of common cause failures

Test interval	Test interval (hours)	Unavailability type 1 design	Unavailability type 2 design	Unavailability type 3 design
1 shift	8	0.010%	0.007%	0.005%
1 day	24	0.029%	0.020%	0.016%
1 week	168	0.200%	0.140%	0.110%
1 month	720	0.870%	0.610%	0.490%
1 quarter	2,160	2.610%	1.840%	1.490%
6 months	4,320	5.220%	3.690%	3.030%
1 year	8,760	10.580%	7.540%	6.390%
18 months	12,960	15.660%	11.220%	9.780%
2 years	17,520	21.160%	15.270%	13.720%

Table 6. Reliability of different level interlock configurations

Configuration class	Redundancy	Test interval	Reliability, %	SIL
Type 3	Fully	Monthly	99.5	2
		Quarterly	98.5	1
		Annually	93.6	1
Type 2	Final Element	Monthly	99.4	2
		Quarterly	98.2	1
		Annually	92.5	1
Type 1	None	Monthly	99.1	2
		Quarterly	97.4	1
		Annually	89.4	0

ISA 84.01 SIL reliability requirements shown in Table 7 enables the designer to take into account cost-benefit considerations between initial capital cost and ongoing maintenance cost.

For example, a SIL 1 might be achieved using a Type 1 configuration with monthly function testing or a Type 2 configuration with annual testing.

A RECENT CASE STUDY

The methodology outlined in this paper was recently used to optimize a flare system in an operating large refinery. The refinery needed to add more than twenty large relief loads from atmospheric vents on several existing columns to the flare system. Additional flare loads from a new planned unit expansion needed to be connected to the existing flare system as well. The design plans called for relocating the flare stack and for expanding the additional new main header piping to 122 cm (48 inch) diameter. The refinery did not want to modify the existing main flare header or any of the existing seven sub-headers. A total of 340 relief devices were connected to the main flare system.

After careful optimization of two of the seven sub-headers connected to the main flare header, the main flare header calculated actual flow capacity was 890,000 kg/hr vs. a requirement of 1,340,000 kg/hr. At a flow capacity of 890,000 kg/hr several large vessels would exhibit pressures up to 1.7 times the maximum allowable working pressure.

Table 7. Combining results with the ISA 84.01 SIL

Safety integrity level	Availability range, %
1	90–99
2	99–99.9
3	99.9–99.99

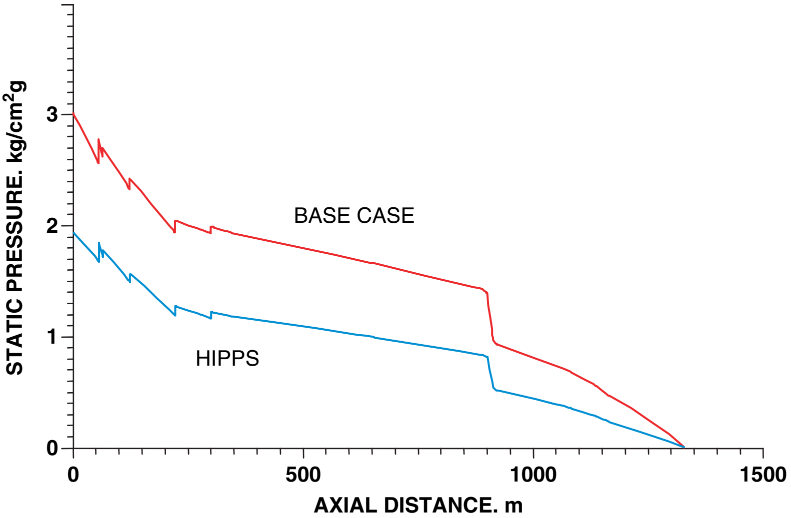

Figure 1. Main header pressure profile

Twelve HIPS systems with SIL levels of 1, 2, 2 + 2, and 3 were selected and optimized such that (a) all connected equipment comply with code requirements for pressure and temperature accumulation when ALL the HIPS function on demand, (b) it is not possible for any simultaneous failure of one or more HIPS to cause code violations at a frequency that exceeds the established target tolerability frequency, and (c) thermal radiation and noise criteria are met under both conditions a and b.

Profiles of pressure in the main header as well as the thermal radiation contours are shown in Figures 1 and 2 for the optimized flare system. Note the length of the main flare header. The HIPS solution enabled the refinery to maximise use of the existing flare structure and ensured continued safe operations with significant additional loads on the flare system. With HIPS, a cost optimal risk reduction was achieved easily and quickly.

CONCLUSIONS

The use of advanced pressure relief dynamics tools such as SuperChems™ Expert can provide accurate estimates of flaring loads and flare systems performance. When coupled with proper risk analysis techniques, accurate flow dynamics provide an optimal cost-risk reduction benefit of where and how to use safety instrumented systems (HIPS). This will yield a safe and cost effective design that meets code requirements for the best-case scenario (all systems working as designed) and that meets social and corporate risk tolerability criteria for worst-case scenarios (when one or more systems fail on demand).

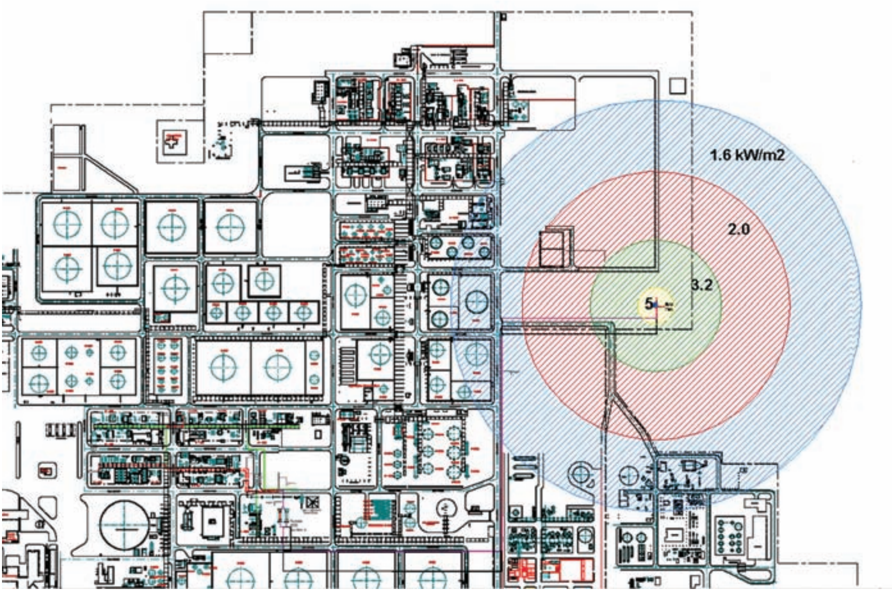

Figure 2. Flare system thermal radiation hazard zones at ground level

Risk tolerability criteria needs to account for the hazardous effects of accumulation on pressure vessels. Designs that result in a vessel accumulation >300% should not be allowed or considered. Note that SIL levels can be enhanced using shorter testing intervals.

The use of many existing flare structures can be maximized using the risk based approach outlined in this paper.

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