QRA and ERS: an Integrated Approach.

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ABSTRACT

Quantitative Risk Analysis (QRA) and Emergency Relief System (ERS) Analysis are both components of a successful Process Safety Management Program. While both studies often share the same information, they tend to remain separate, independent, studies. However, at facilities where relief valves can vent toxic and flammable materials directly to the atmosphere, these discharges can be a significant contributor to overall risk.

ioMosaic Corporation has recently performed studies combining QRA and ERS techniques, for major chemical companies. The integrated approach realized many benefits. Efficiency was gained in terms of data collection, data sharing and information management. The existing Emergency Relief System was analyzed for its adequacy; while the Quantitative Risk Analysis considered various hazard scenarios throughout the plant, including relief device discharge.

Using a case study, this paper outlines the methodologies used, and the risk mitigation options proposed. The original projects contain proprietary business information, which has been appropriately edited for the purposes of this paper.

INTRODUCTION

The historical reasons for the separation of QRA and ERS analysis are numerous, and vary from company to company; though there are a few common themes:

1. Budgetary and Departmental constraints. While it is common for ERS projects to be funded by individual operating units, QRA projects tend to be funded through central engineering, or risk management departments. Often the opportunity to combine such studies and share relevant resources is lost due to lack of communication, or bureaucratic budgeting systems.

2. Lack of specific expertise. Differing areas of expertise may lead an ERS design engineer to shy away from suggesting QRA; or vice versa. Even when this work is outsourced to contracting companies, the contracting firm may not possess expertise in both areas.

3. QRA is not regulated in the US and many other countries, while many aspects of ERS are regulated. There exist very well established and accepted design standards, practices and guidelines for both ERS analysis, and QRA.

   With ERS, the primary regulatory drivers in the US are:

   i. OSHA Title 29, Chapter XVII, Part 1910
   ii. ASME Section VIII
   iii. ASME Section I
   iv. ASME B31.1 and B31.3

   The established codes and practices for ERS include:

   i. API RP 520, Parts I & II
   ii. API RP 521
   iii. API STD 526
   iv. API STD 2000
   v. NFPA-30
   vi. CCPS, '*Guidelines for Pressure Relief and Effluent Handling*'

   QRA is not enforceable as a regulatory requirement in the USA. Furthermore, the use of phrases such as "probability of fatality" and "number of fatalities" tends to dissuade companies, from a liability standpoint. QRA does have well established guidelines, however, including:

   i. CCPS, '*Guidelines for Chemical Process Quantitative Risk Analysis*'
   ii. Committee for the Prevention of Disasters, '*Guidelines for Quantitative Risk Assessment' – (Purple Book)*

4. The tools and software for analysis are different and not readily transferable. ERS calculations tend to use different software tools compared with QRA calculations. If so, this information is not readily transferable, and would require significant duplication of effort. In the case study described in this paper however, SuperChems Expert™ enabled calculations to be performed on one integrated software platform, and significant efficiency gains were able to be realized.

REASONS FOR INTEGRATION

Although QRA and ERS studies are not commonly integrated, it is also worth considering the potential efficiency gains which can be achieved if they are integrated.

There is significant overlap of information, with both analyses requiring:

- Piping & Instrumentation Diagrams
- Process Flow Diagrams
- Heat & Material Balances

In addition, both analyses also require: mass flowrates, mixture compositions, operating temperatures and pressures, storage inventories, release elevations, nominal pipe sizes, and release orientation. Therefore, properly planned data gathering *and subsequent management of this data*, can significantly reduce duplication of effort, as the project progresses.

Finally, the contingency analysis that is performed during an ERS study can be useful in defining some of the release scenarios for QRA. Additionally, both QRA and ERS involve comparison of safeguards and mitigation techniques which often have overlapping (or interacting) effects on each other. The best alternative for ERS, taken as a standalone evaluation, may not be the most cost effective when overall QRA is considered.

BACKGROUND

This case study considers a specialty chemical manufacturing plant where it was possible to combine the QRA and ERS methodologies. The plant manufactures a variety of specialty chemicals which are utilized by a broad spectrum of industries. The plant is operated 24 hours a day, seven days per week, with over 500 full time employees at the site. The facility is rurally situated.

Onsite, the plant stores a wide variety of toxic chemicals in excess of the threshold quantities, some of which include: Anhydrous Ammonia, Acrylonitrile, Propylene oxide, and Methyl chloride. The plant also stores several flammable chemicals above threshold quantities as defined by OSHA regulations in the US.

THE QUANTITATIVE RISK ANALYSIS STUDY

The scope of the project originally set out to provide just a Quantitative Risk Analysis. However, as the study progressed, the initial findings led to a decision to combine approaches, and include ERS analysis.

The initial QRA objective was to determine both on-site and off-site risk, for the plant. Results would be presented in terms of both individual risk, and societal risk. Additionally, risk reduction opportunities were identified. As will be demonstrated in this paper, the risk reduction section led to the subsequent emergency relief systems design analysis.

The QRA was conducted using a typical approach:

- Hazard Scenarios Development
- Frequency Analysis
- Consequence Analysis
- Risk Determination

Hazard Scenarios Development

The scope of the QRA was limited to seven chemicals which were determined to pose the greatest risk. Based on previous process hazard analysis (PHA), and historical incidents at the facility, a list of scenarios was developed. The primary scenarios to be considered were:

- Vessel failure
- Line failure
- Relief device failure open
- Overfilling
- Hose failure
- External fire
- Contamination
- Mischarge
- Failure of heating or cooling medium
- Loss of inert gas

The final list of chemicals, and the number of relevant scenarios developed, is shown in Table 1 below:

Table 1: Chemicals included within QRA scope.

Chemical	Flammable	Toxic	Number of Scenarios
Chemical A	Y	N	7
Chemical B	Y	Y	14
Chemical C	Y	Y	11
Chemical D	N	Y	7
Chemical E	Y	Y	13
Chemical F	Y	Y	17
Chemical G	Y	Y	14

Frequency Analysis:

The frequency analysis of each scenario was conducted using the layer of protection analysis (LOPA) technique that is described in the CCPS publication '*Layer of Protection Analysis, Simplified Process Risk Assessment'.* There are advantages to using LOPA verses more traditional risk assessment methodologies such as fault tree analysis:

- LOPA facilitates the determination of more precise cause-consequence pairs, and therefore improves scenario identification.
- The frequencies and probabilities provided in the CCPS LOPA text reflect the most recent consensus of data from companies in the chemical process industries since the book was published in 2001. This data does not require extrapolation of old data to current equipment or data developed from other industries (i.e., nuclear) to the chemical industry.

For each scenario developed, the frequency of the event that produces the described consequences was determined. Each overall scenario frequency may consist of a number of events:

- The **initiating event** which causes an undesirable deviation from normal operation. This could be a human error, equipment or instrument failure or external event, such as fire. The initiating event may be expressed as an annual frequency or as a probability per opportunity. For example scenarios that have an initiating event based on human error are typically expressed as a failure rate per opportunity. The enabling event would then be expressed as the number of opportunities per year (frequency).
- An **enabling event** which is typically related to time the system is exposed to the undesirable deviation while it is in a hazardous state. An example would be failure of an unloading hose on a trailer due to the cab pulling away while still connected. If the trailer is empty when this happens, then no spill of hazardous chemical will result. The enabling event is typically expressed as a probability, but may also be expressed as a frequency when the scenario involves human actions that are done at repetitive intervals.
- The number of similar **units** that could experience the same scenario. These could be the number of vessels or equipment or length of piping.
- A **conditional event** that must occur for the undesirable consequences to result. An example is a failure to purge a vessel containing flammable material with nitrogen prior opening for maintenance. If the undesirable consequences are a fire, then the conditional event is the ignition of the flammable vapors in the vessel. A conditional event is included in the scenario frequency when the event is taken to a pre-defined consequence. Most loss of containment scenarios involving flammable materials do not

include the conditional event in the frequency, but rather is developed as part of an event tree that evaluates all possible consequences including: no ignition, immediate ignition, and delayed ignition. This event tree analysis was also considered when setting up the QRA. A conditional event is expressed as a probability.

- An **independent protection layer (IPL) event** that either prevents or reduces the likelihood of the scenario. An IPL is expressed as a probability of failure on demand.

An IPL is a device, system, or action that is capable of preventing a scenario from proceeding to its undesired consequence independent of the initiating event or the action of any other layer of protection associated with the scenario. In order to be considered an IPL, the device, system or action must be:

- Effective in preventing the consequence
- Independent of the initiating event and the components of any other IPL
- Auditable through validation of design and effectiveness

A typical scenario frequency analysis, outlining the initiating causes and likelihood of failure is shown in Table 2 below.

Table 2: Sample frequency analysis.

Frequency Summary	Description	Value
QRA Reference	Chemical G External Fire	
Initiating Event (frequency per unit)	External Fire on a vessel containing Chemical G	1.00 E-02
Units	One Vessel	1
Enabling Event (probability)	Continuous Service	1
IPL 1	Emergency response to extinguish fire before contents of tank reaches runaway temperature of 200ºC	1.00 E-01
IPL 2	Water sprays limit temperature of tank to 100ºC	1.00 E-01
IPL 3	None	1
Scenario Frequency		**1.00 E-04**
Comments	1. No credit is taken for insulation on the tank, as it is not specified to be fire-rated.	
	2. It is assumed that the PSV was sized for fire, and is not adequate to relieve a runaway reaction.	

As described in the CCPS LOPA book, some items such as procedures, training and mechanical integrity would be factored into the initiating event frequency, but are not considered IPLs. Similarly, fire protection is typically considered in determining the duration of the event, except for external vessel fires which allow for emergency response before the vessel relief device opens. The vessel relief devices were not considered as IPLs, as the relief device discharging to atmosphere contributed to the risk calculation. Additionally, as stated in Table 2, it was assumed that the relief devices were sized adequately for fire; but not for runaway reaction, which would lead to loss of containment of the entire vessel.

This study used the approach as defined in the LOPA text which allows more than one IPL to be in the same Basic Process Control System (BPCS) or a BPCS IPL with a BPCS initiating event. This approach is based on the assumption that if a BPCS function fails, it is much more probable that the component that induced the failure is the detection device or the final control element and not the logic solver.

Where historical plant failure rates were available, this information was used in place of the generic values available in the CCPS LOPA text. Where neither source provided appropriate data, appropriate values were developed based on other proprietary sources or good engineering judgment.

Consequence Analysis

In conducting the Quantitative Risk Analysis, SuperChems Expert™ was used to model consequence results, risk results, and the subsequent Emergency Relief Systems modeling.

Local wind rose statistics were gathered, based over a three year period with sixteen wind directions; and dispersion results were generated for three different atmospheric stability classes: B, D, and F.

The discharge models providing source term calculations, calculated actual release duration based on storage inventory, and release rate. This release duration was then carried forward to the dispersion models. Existing mitigation measures, such as dikes, emergency response, and isolation, were accounted for when modeling release spread, and release duration.
Day and night on-site and off-site population and ignition sources were defined. On-site population information was provided by the client; off-site population was provided by the 2000 Census demographic data contained in LandView® 6.

The study considered consequences arising from thermal radiation, overpressure, and toxicity. Risk effects were modeled based on dose-based probit calculations. For the purposes of the consequence analysis, commonly accepted criteria were reported; including thermal radiation values of 4, 12.5, and 37.5 kW/m^2; and explosion overpressure values of 2.07, 6.9, and 20.7 kPa. For toxic effects, three Emergency Response Planning Guideline (ERPG) values were reported, signifying differing levels of harm based on a one hour exposure time.

Approximately 1100 possible hazard outcomes were generated, which considered release scenario, wind speed and direction probability, atmospheric stability category, and immediate or delayed ignition. These 1100 outcomes were then used in the risk determination.

Risk Determination

Both Individual and Societal Risk results were modeled, as shown in Figures 1 and 2. Onsite and Offsite effects were calculated, with results presented for daytime, night-time and combined.

Additional onsite risk statistics were also calculated showing the highest individual risk, average individual risk, fatal accident rate, and rate of death.

Where:

Individual Risk: "The risk to a person in the vicinity of a hazard. This includes the nature of the injury to the individual, the likelihood of the injury occurring, and the time period over which the injury might occur".

Average Individual Risk: "The average of all individual risk estimates over a defined population".

Fatal Accident Rate (FAR): is calculated from the average individual risk, and is normally used as a measure of employee risk in an exposed population. This is the number of fatalities occurring during 1000 working lifetimes (10^8 hours).

Average Rate of Death (ROD): is the estimated average number of fatalities in the population from all potential incidents.

Each of the 1100 scenario outcomes could also be sorted, and ranked in terms of their contribution to the overall risk. Ranking these outcomes would play a crucial role in determining the most appropriate risk mitigation options.

Figure 1. Overall Individual Risk Results. Base Case.

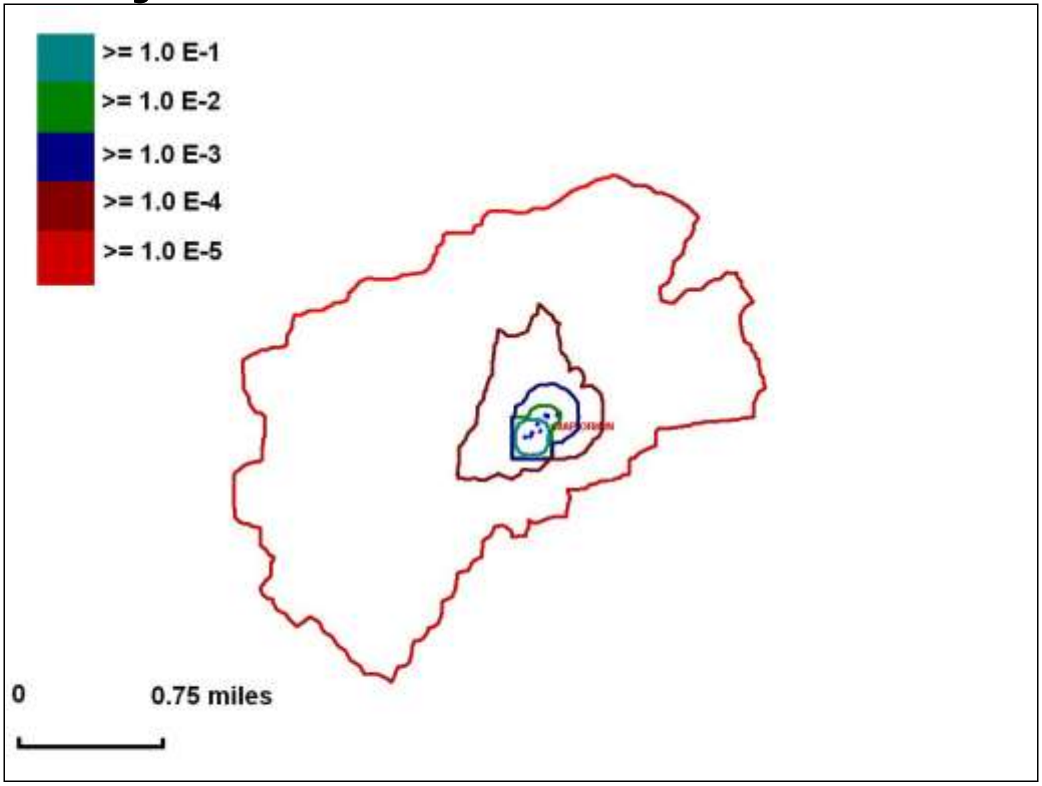
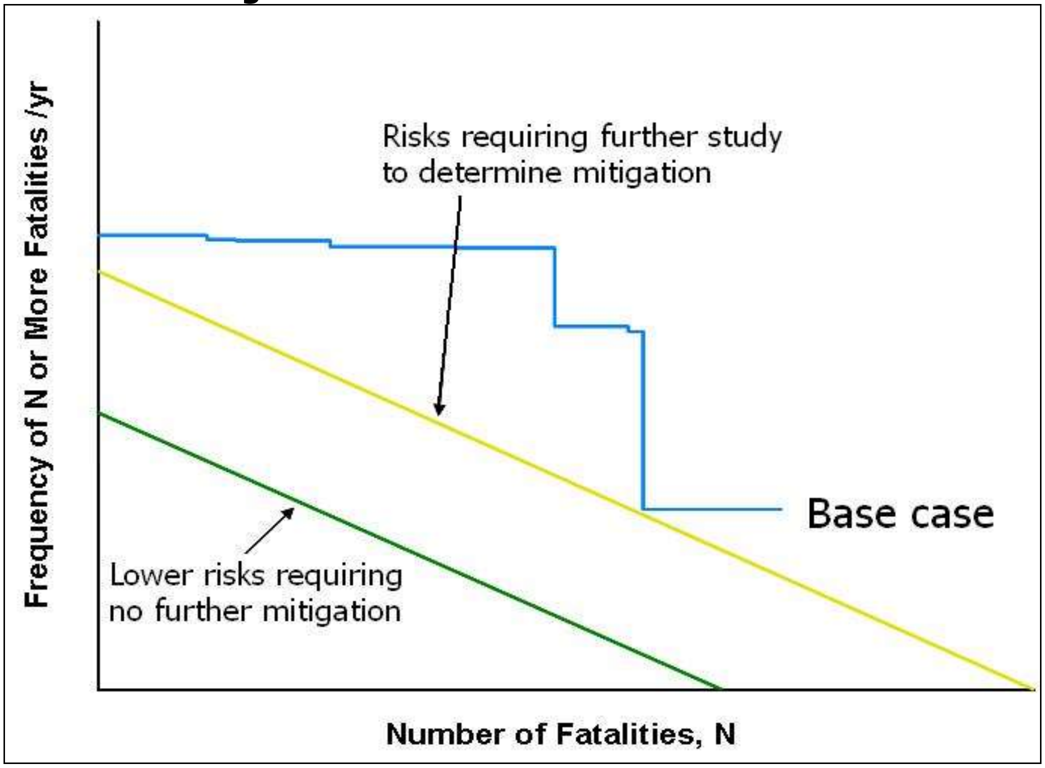


Figure 2. Overall Societal Risk Results.



Risk Discussion

For both the Individual Risk, and the Societal Risk; the risk results exceeded the client's tolerable levels. In Figure 2, the Dutch Government risk criteria lines were overlaid, to give a basis for comparison. As can be seen, the calculated base case F-N curve significantly exceeds the risk criteria line representing "Risks Requiring Further Study to Determine Mitigation".

Scenario outcomes were ranked based on their risk, which revealed that the risk profiles were dominated by toxic releases to atmosphere, from pressure safety valves (PSVs), due to process induced runaway reactions, fire exposure, or fire induced runaway reactions.

The main PSV-related risk contributors were identified and prioritized:

- External fire leading to relief device actuation
- Contamination leading to relief device actuation
- Loss of heating and/or cooling leading to relief device actuation
- Relief Valve Failure Open
- Uncontrolled polymerization leading to relief device actuation

It is interesting to note that, for the seven chemicals considered in the analysis, the US EPA Envirofacts database of significant incidents lists six 'Stack or Point Emissions' occurring in the year 2004, with 900 kilograms of a toxic substance representing the largest release amount. It can therefore be deduced that relief device discharges can, and do, occur on a fairly regular basis

If the main ERS-related scenarios were mitigated/eliminated by installation of an effluent handling system consisting of a catch tank and an associated flare stack, the offsite risks could be reduced significantly. In order to successfully implement this mitigation measure, a full Emergency Relief System Design analysis was undertaken, to accurately determine all the relief loads which would affect the proposed effluent handling system.

THE EMERGENCY RELIEF SYSTEM DESIGN STUDY

The scope of the emergency relief system design study was limited to the items which would be routed to the proposed flare stack. Those items had been identified as significant risk contributors during the QRA phase.

The emergency relief system design study was performed, according to the following workflow:

- System-specific Emergency Relief Systems Evaluation
  - Overpressure contingency analysis
  - Determination of required relief rates
  - Capacity rating of existing relief system
- Effluent Handling System Evaluation
  - Common failure mode scenarios
  - Effluent Handling System Hydraulic Analysis
  - Catch tank design

System-specific Emergency Relief Systems Evaluation

API RP 521 provides very thorough guidance on overpressure contingency analysis, determination of relieving rates, and disposal systems. Table 2, of API RP 521 lists the following upset conditions, which may result in overpressure:

- Closed outlets on vessels
- Cooling water failure to condenser
- Top-tower reflux failure
- Sidestream reflux failure
- Lean oil failure to absorber
- Accumulation of non-condensables
- Entrance of highly volatile material
- Overfilling storage or surge vessel
- Failure of automatic controls
- Abnormal heat or vapor input
- Split exchanger tube
- Internal explosions
- Chemical reaction
- Hydraulic expansion
- Exterior fire
- Power failure

Using this list as a basis, it was possible to develop a matrix of overpressure scenario, cross-referenced to specific vessel types, as shown in Table 3:

Each individual emergency relief system was verified for adequacy. Where applicable, emergency relief system discharges were considered for either vapor, liquid, or two-phase flow. Inlet pressure drop was limited to 3% of the set pressure; the API recommended maximum value for both compressible and incompressible fluid flow. Outlet pressure drop for conventional type pressure relief valves was limited to the allowable overpressure for the contingency under consideration (usually 10% for process-related overpressures, and 21% for fire exposure).

Relief device outlet piping was redesigned in such a way that the discharge lines would connect together to form sub-headers, which in turn, connected to the proposed header. This header led to a catch tank, which would remove any harmful liquid toxic components, while safely burning the vapors via a flare stack.

For each relief device, the required flowrate, chemical composition, phase, temperature, and pressures for each piping segment; was taken forward to the Effluent Handling System Evaluation.

Table 3: Common contingencies cross-referenced to type of equipment

	Closed Outlets	Cooling Failure	Reflux Failure	Accumulation of Noncondensables	Mixing of Volatile and Hot Materials	Failure of Automatic Controls	Abnormal Heat or Vapor Input	Internal Explosions	Chemical Reaction	Hydraulic Thermal Expansion	Exposure to External Fire	Ruptured heat exchanger tube	Power / Utility Failure	Inadvertent Valve Opening	Transient Pressure Surges	Inbreathing/Outbreathing
Blower	☑												☑			
Boiler	☑										☑		☑			
Column - Packed	☑	☑	☑			☑	☑				☑		☑	☑		
Column - Trayed	☑	☑	☑			☑	☑				☑		☑	☑		
Compressor - Centrifugal	☑												☑			
Compressor - Positive Displacement	☑												☑			
Dryer	☑				☑	☑				☑	☑		☑	☑		
Filter	☑					☑				☑	☑		☑	☑		
Fired Heater	☑												☑			
Heat Exchanger - Aerial	☑					☑					☑		☑			
Heat Exchanger - Concentric Pipe	☑					☑				☑	☑		☑			
Heat Exchanger - Electric	☑					☑				☑	☑		☑			
Heat Exchanger - Other	☑					☑				☑	☑		☑			
Heat Exchanger - Plate and Frame	☑					☑				☑	☑		☑			
Heat Exchanger - Shell and Tube	☑					☑				☑	☑	☑	☑			
Pipe Segment	☑									☑			☑			
Pump - Centrifugal	☑												☑			
Pump - Positive Displacement	☑												☑			
Reactor	☑	☑				☑			☑		☑		☑	☑		
Storage Tank	☑					☑					☑		☑	☑		☑
Storage Vessel	☑					☑					☑		☑	☑		
Turbine	☑												☑			
Vessel	☑					☑					☑		☑	☑		

Effluent Handling System Evaluation

The overall goal of the Effluent Handling System Evaluation was to determine the adequacy of the system in the event of various common failure mode scenarios. Adequacy of the flare header, flare tip design, liquid separation equipment, and radiation intensity was considered for each identified common failure mode scenario.

The Effluent Handling System Evaluation also considered the various chemicals being released, to ensure there would be no undesired reactions occurring in the proposed catch tank.

Common Failure Mode Scenarios

A common failure mode scenario is considered a single event that may result in the overpressure of more than one emergency relief system impacting the effluent handling system. Typical common failure mode scenarios include loss of a single utility (cooling water, instrument air, steam, electricity, etc.) that adversely affects multiple systems. Note that for all common failure mode scenarios it was assumed that all control systems potentially venting to the flare are closed with no additional vapor load.

Common Failure Mode Scenarios were assessed for:

- External Fire
- Power Failure (total & partial)
- Cooling Failure (Glycol, Water)
- Utility Failure (Instrument Air, Steam, Nitrogen)

Details of one of the common fire scenarios are given below. A similar analysis was performed for each applicable common failure mode scenario.

External Fire

External pool fires were assumed to be circular and have a maximum diameter of 56 ft, equivalent to a maximum fire zone area of 2,500 ft^2, and encompassing major equipment items.

Table 4: Fire Scenario "1" Hydraulic Results

Relief Device	Device Type[1]	Protected Equipment	Set Pressure (psig)	Relief Requirement (lb/h)	Relief device capacity (lb/h)	Actual node flow (lb/h)	Percent of Max. Flow	Remains Adequate? (Y/N)
PSV-1	**C**	**TK-1**	**70**	**11000**	**12500**	**7000**	**56**	**No**
PSV-2	B	TK-2	15	11000	15000	14000	93	Yes
PSV-3	B	TK-3	15	6000	11500	7250	63	Yes
PSV-4	B	TK-4	15	11500	15500	13000	84	Yes

Note 1: C = Conventional, B = Bellows, P = Pilot

Based on the hydraulic analysis shown in Table 4, the relief capacity for relief device PSV-1 on TK-1 may be reduced beyond the relief requirement. To mitigate the potentially excessive backpressure concern:

- Consideration was given to reducing the relief requirement by taking credit for the maximum actual operating wetted area of TK-1; rather than the relief requirement being based on an assumption that the tank may operate 80% liquid full.
- Consideration was also given to PSV-1 being modified to a balanced-bellows type relief device.
- Additionally, the outlet piping could have been modified by increasing the line diameter, to alleviate the excessive outlet pressure drop.

It was also noted that the flow capacity through PSV-3 was derated significantly; though the relief device remained adequate.

Catch Tank Design

The main principle of the catch tank is to first separate and contain the liquid released, and then to pass the vapor for further treatment. Typical separation equipment that is used includes:

- Horizontal separators (gravity)
- Vertical separators (gravity)
- Cyclone Separators
- Quench tanks (open)
- Impingement separators

In the case study presented, a vertical separator was selected. The header catch tank was evaluated for all identified common failure mode scenarios. API RP 521 recommends a liquid retention time of 20-30 minutes with a maximum particle diameter at the outlet of the drum of 300-600 microns. The proposed catch tank was evaluated based on these criteria.

In order to meet the desired design criteria a vertical separator would require the following design conditions:

Table 5: Vertical Separator Sizing for Fire Scenario "1"

Catch Tank (Fire Scenario "1")	Required (ft)
HME: Mist eliminator adjustment. ft	0
HD: Minimum height required for disengagement. ft	3.35
HLN: Height from HLL to nozzle centerline. ft	1.35
TOTAL	4.70
HS: Height from NLL to HLL. Surge height. ft	0.50
HH: Height from LLL to NLL. ft	0.95
HLLL: Low liquid level height. ft	1.25
TOTAL	2.70
Separator length. ft	**7.40**
Separator diameter. ft	**3.70**

Flare Tip

Finally, for each Common Failure Mode Scenario, the conditions at the flare tip were assessed. The exit velocity is evaluated at the flare tip. It is generally recognized practice that the upper limit is Mach number 0.6. Based on the proposed flare elevation; the thermal radiation as shown in Figures 3 & 4, was found to be within the limits prescribed by API-521 presented in Table 6:

Table 6: Recommended Design Total Radiation

Permissible Design Level (kW / m²)	Conditions
15.77	Heat intensity on structures and in areas where operators are not likely to be performing duties and where shelter from radiant heat is available
9.46	Heat intensity at any location to which people have access, with limited exposure time (few seconds) and where escape is possible
6.31	Heat intensity where emergency actions lasting up to 1 minute may be required by personnel with appropriate clothing, but without heat shielding
4.73	Heat intensity where emergency actions lasting up several minutes may be required by personnel with appropriate clothing, but without heat shielding
1.58	Heat intensity where personnel with appropriate clothing may be continuously exposed

Source: API Recommended Practice 521, 4th edition; Table 8

Figure 3: Vertical Radiation Profiles for Fire Scenario "1".

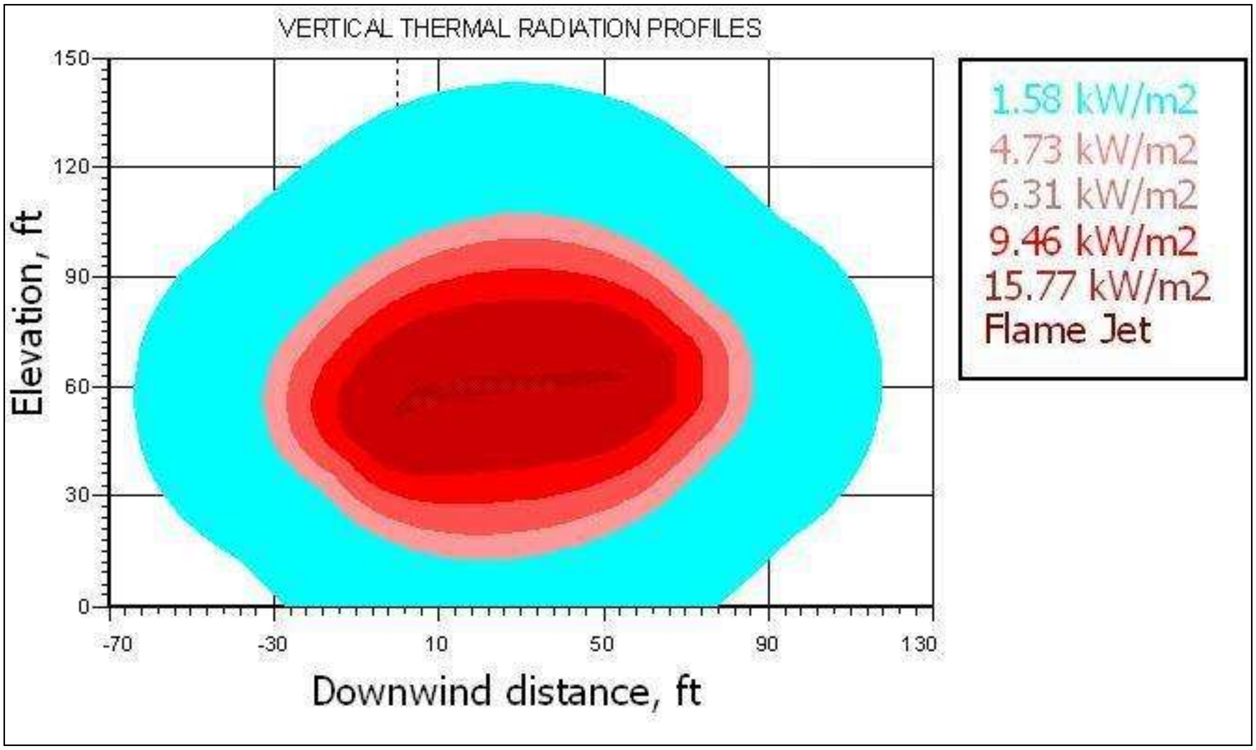
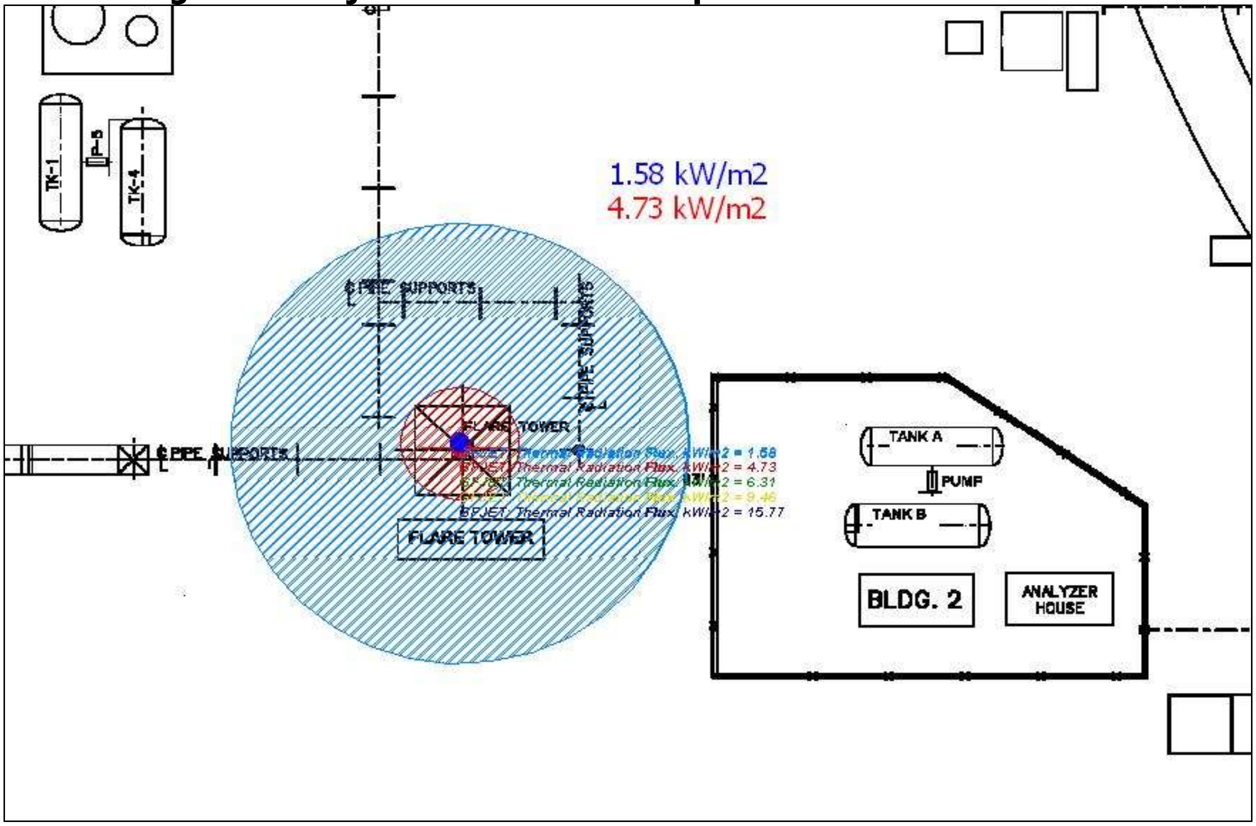


Figure 4: Projected Radiation Footprint for Fire Scenario "1".



The Effluent Handling System Evaluation was repeated for each applicable common failure mode scenario, to ensure adequacy of the piping network and optimum design for the catch tank.

Upon completion of this stage of the project, it was possible to revise the Quantitative Risk Analysis accordingly.

Revised Risk Calculations

The existing QRA study was revised, with relief device discharge outcomes removed from consideration. Additionally, the catch tank was included within the study scope.

Revised risk results were now found to be as follows:

Figure 5. Overall Individual Risk Results. Mitigated Design.

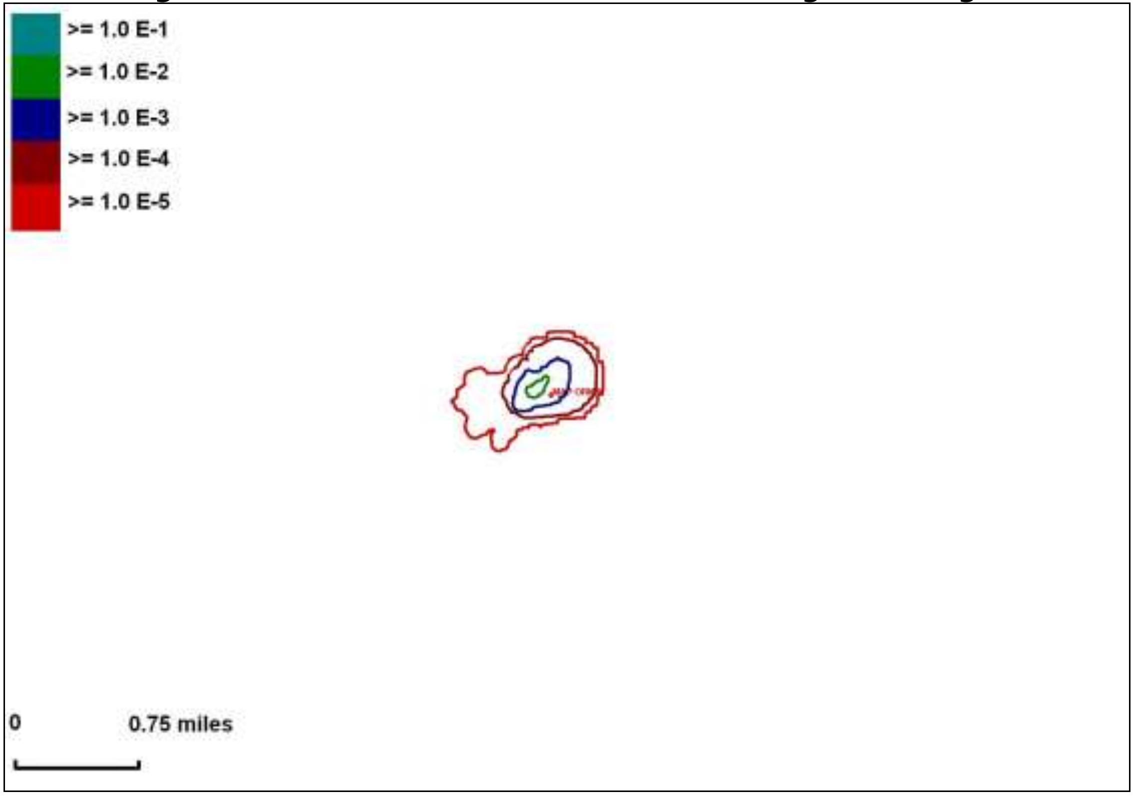
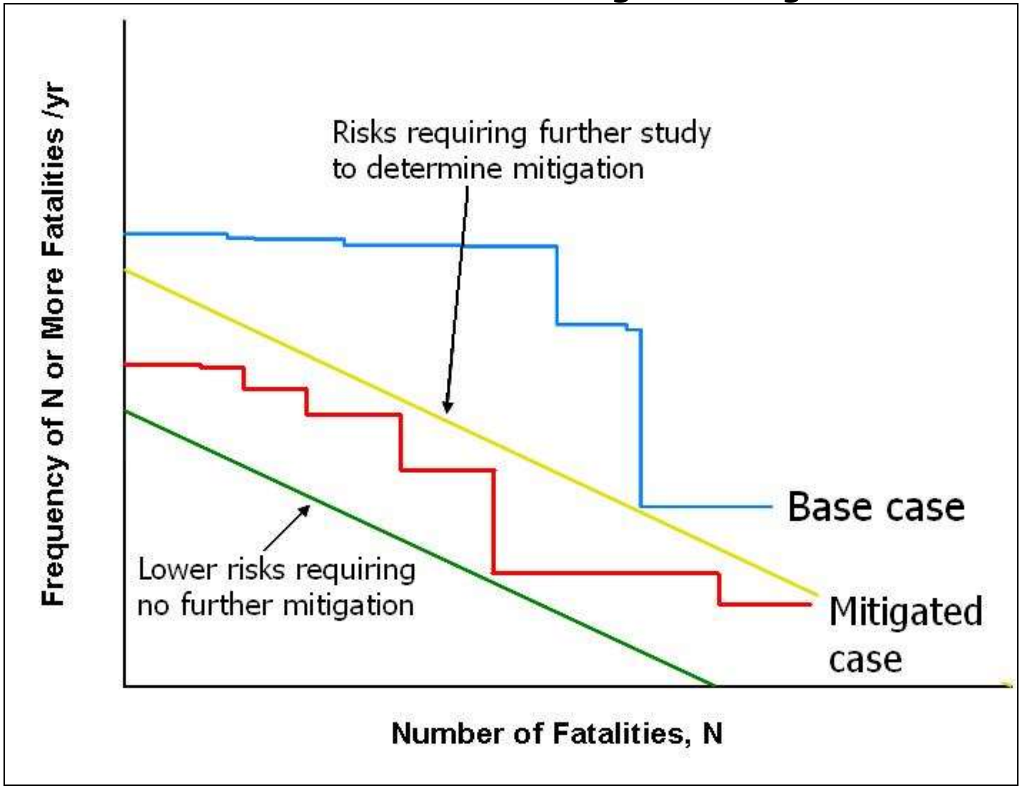


Figure 6. Overall Societal Risk Results. Mitigated Design and Base Case.



CONCLUSIONS

As can be seen in Figures 5 and 6, compared with the base case Figures 1 and 2; the implementation of a properly designed effluent handling system has significantly reduced the risk to within tolerable levels.

While the chemical industry is currently placing considerable focus on replacing atmospheric discharge relief devices with appropriate effluent handling systems, it is not often that their benefits are quite as obvious as demonstrated by this case study.

SuperChems Expert™ enabled these two studies to be combined efficiently on one integrated software platform. The client benefited by implementing significant risk reduction measures, while receiving up-to-date QRA and ERS studies, which can easily be updated should the existing arrangement ever change.

A combined QRA and ERS approach offers an innovative and accurate option to any company interested in reducing their risks.

References:

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2. API Recommended Practice 520 – Sizing, Selection, and Installation of Pressure Relief Devices in Refineries – Part I (2000).

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4. API Recommended Practice 521 – Guide for Pressure Relieving and Depressuring Systems (1997).

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9. Bellomo, P. J., and Stickles, R. P., (1995) "Select Design Bases for Emergency Relief and Other Process Safety Systems Based on Risk", proceedings from International Symposium on Runaway Reactions and Pressure Relief Design, pp. 631 – 647.