Improving Refinery Safety using Quantitative Risk Assessment and the Role of Software

Introduction

Quantitative Risk Assessment (QRA) in the context of hydrocarbon engineering is a methodolgy for quantifying the risks associated with the activities involved in the production and processing of petrochemicals. In order to quantify risks it is necessary to first identify all possible risk situations, quantify them in terms of event consequence and frequency and compare them with acceptable criteria. The main questions to be answered are what can go wrong, what will the effects be if it does go wrong, how often will it go wrong and is it important if it goes wrong. Or, in QRA terms, identify the hazards, analyse the consequence, estimate the frequency, combine consequence and frequency to assess and manage the risk. The key objectives of any QRA are to identify the major hazards, quantify the overall risk, optimise the risk reduction measures to be implemented and to help the decision making process with regard to acceptable risk criteria.

Why QRA

There are many reasons for performing a QRA and equally as many benefits to be had. QRA can be used as a way of maximising safety at minimum cost, it can be used as part of developing safety cases, or it may be a requirement of the particular legislative regime within which a plant operates. There may also be risk exposure criteria which are acceptable for insurance purposes which have to be satisfied or it may be useful purely from a decision making standpoint. QRA combined with an effective safety management system can act to both improve safety and reduce costs. It is of particular benefit when identifying the most effective risk reduction measures. By clearly identifying the areas of highest risk, it allows effort to be focused on them. When a risk reduction measure is proposed, its effect can be clearly illustrated by modifying the QRA model and recalculating the risk levels to assess how effective this measure has been. Using this methodology the benefits of a variety of risk reduction measures can be compared and the most effective combination can be

implemented. Also, by including cost estimation for each suggested risk reduction measure, a cost benefit element can be included in the QRA to determine which measure, or combination of measures, will be most cost effective

Why Software?

In order to perform an effective QRA it is essential that all possible accident scenarios are taken account of so that potential sources of high risk are not omitted from the overall risk picture. This means that QRA's rely on large quantities of accurate data and the performance of many repetitive calculations and risk summations. Also, in order for the QRA results to be as accurate as possible, well developed state-of-the-art mathematical models must be used to calculate the consequences of each scenario and feed into the overall risk calculations. In the past, computer technology was such that expensive mainframes or workstations were required to perform these calculations. However, as technology has moved forward, hardware has become much more powerful at much lower cost. Also, system software such as operating systems, databases and development environments has become much more powerful, enabling software developers to provide far more user friendly solutions. It has become possible over the last few years to make consequence modelling tools, such as PHAST, and full QRA packages, such as SAFETI, accessible on hardware and operating systems that are available to far more analysts. Also, as models become better validated and evolve to give more accurate results and tools become more user friendly and robust, they no longer necessarily need 'expert' users. That is not to say users no longer need to understand consequence and risk. However, they no longer need to understand how the data is handled, the variety of operating systems under which they run and the architectural and navigational anomalies previously necessary to 'shoe-horn' the applications into the available hardware and software platforms.

QRA Methodology for Onshore Risk

There are five major components to a classically structured risk analysis study. These are

- Identify the hazards and define the failure cases
- Estimate the frequencies with which these failures occur
- Model the consequences of failures
- Analyse the risks
- Assess risks and incorporate risk reduction measures

This process is summarised in Figure 1.

DNV uses its SAFETI (Software for the Assessment of Flammable, Explosive and Toxic Impacts) Risk Analysis software as its core tool for onshore risk studies. This was developed in partnership with the Dutch Government in the early 1980s and, since then, it has been expanded and enhanced to a very high degree. It is now regarded as by far the most comprehensive quantitative tool for assessing process plant risks. SAFETI incorporates PHAST (Process Hazard Analysis Software Tools) for consequence modelling.

SAFETI is designed to perform the analytical, data processing and results presentation elements of a QRA within the framework described in Figure 1. Its primary functions are:

- to enable the assessment of the whole range of failures that are possible (including small-frequent, medium-unusual, and catastrophic-rare incidents)
- to allow the input of frequencies for all failures defined
- to model realistically all possible event outcomes (pool fire, jet fire, flash fire, vapour cloud explosion, safe unignited dispersion, etc.)
- to model toxic releases affecting people onsite and offsite people
- to determine the total risk
- to determine the relative importance of various release cases in generating an overall plant risk
- to assess the value of extra risk reduction investment in conjunction with a cost-benefit approach

The key benefit of Software QRA is the ability to identify major risk items and differentiate these from worst case incidents that otherwise might tend to dominate safety reviews. It is often found that scenarios that result in the most serious consequence are not usually the major risk contributors. Time and effort directed to mitigating high consequence but often low frequency events has therefore not been well spent.

QRA, by combining the likelihood of each incident with a detailed calculation of its consequence, will often identify medium scale incidents as the dominant risk contributors. Whilst these have lesser consequences than 'worst-case' events, they have a higher frequency, which, when combined with the consequences, generates a higher level of risk. SAFETI allows every incident to be tracked and its contribution to the total risk evaluated. This allows mitigation measures to be well focused on major risk contributors.

The main inputs to risk assessment are:

- Define loss-of-containment failure cases in terms of size of leak (hole size or rupture), process fluid, temperature and pressure and inventory
- Likelihood of event
- Environmental information (meteorology, ignition data, population data)

Meteorology covers wind speed and direction, topology and atmospheric temperature, pressure and stability. The latter has a major effect on cloud dispersion. Some stability classes are "unstable", particularly those associated with strong sunlight and atmospheric turbulence, which aids rapid dilution. Others are classed as stable, often corresponding to early morning with light wind, and associated with poor atmospheric dilution; these usually cause the most serious consequences. In dispersion analysis, the pairing of atmospheric stability and wind speed is an important factor and worst case scenarios will generally be associated with low wind speed and stable conditions which result in a relatively highly concentrated static cloud.

The SAFETI package enables detailed analysis of this data:

- Each failure case is analysed for all possible consequences including dispersion, pool fires, jet fires, flash fires, BLEVE, vapour cloud explosion and toxic impact
- As dispersion and other events are affected by weather conditions - every event is calculated for all weather conditions and allowed to disperse in a pre-defined number of wind directions
- Every flammable release is passed through an event tree to establish all possible outcomes
- Endpoints in the consequence calculation are the thermal or blast intensities known to cause human casualties
- Toxic releases use a sophisticated "probit" analysis to establish injury / fatality likelihood
- Risks are summed for all events to establish the "Individual Risk" throughout the site and surrounding area
- These are combined with population data to generate "Societal Risk" which is a measure of risk to groups of people rather than to individuals

Measures of Risk

There are two broad types of risk measure, individual risk and societal risk. Individual risk is concerned with levels of risk imposed on individuals, whereas societal risk addresses risks to groups of people without regard to who or where they are. These are two aspects of the same decision process, and both should be considered when performing a QRA.

The UK Institution of Chemical Engineers (1992) defines Individual Risk as "the frequency at which an individual may be expected to sustain a level of harm from the realisation of specified hazards". It is usually taken to be the risk of death and expressed as a risk per year. The most common example of individual risk is the iso-

risk contour. This allows for major hazard areas to be easily identified and the effects on specific vulnerable locations to be more easily observed.

Societal risk provides an indication of the likely severity of an accident. A more formal statement is again provided by the UK Institute of Chemical Engineers (1992), which defines Societal Risk as "the relationship between the frequency and the number of people suffering a given level of harm from the realisation of specified hazards". It is normally taken to refer to the risk of death and expressed as a risk per year.

This is normally displayed as a FN curve, which is one of the most complex quantitative measures developed for regulatory control purposes. It is based on a log-log plot of frequency against number of fatalities. The frequency axis is cumulative, and is expressed in terms of "N or more" rather than the more intuitive "N or less". Although the F-N plot is not as easily understood as individual risk contours, it does present a form of risk that is very important to regulators. Government agencies are particularly concerned about large fatality infrequent events as these cause major disruption to the community. Individual risk does not convey this information and thus decisions based only on individual risk do not address potential disaster scenarios where many may be killed by a single event like, for example, Bhopal.

Risk Criteria

Risk analysis provides a measure of the risk resulting from a particular facility or activity. However, the assessment of the acceptability or otherwise of that risk is left to the judgement and experience of the people undertaking and/or using the risk analysis. The normal approach adopted is to relate the risk measures obtained to acceptable risk criteria.

A quantitative risk analysis produces only numbers but it is the assessment of those numbers that allows conclusions to be drawn and recommendations to be developed. The assessment phase of a study is therefore of prime importance. The simplest framework for risk criteria is a single risk level that divides tolerable risks from intolerable ones. Such criteria give attractively simple results, but they must be used judiciously since they do not reflect the uncertainties both in estimating risks and in assessing what is tolerable.

A more flexible framework for risk criteria is used by the UK HSE. It specifies a level, usually known as the maximum tolerable criterion, above which the risk is regarded as intolerable and must be reduced. Below this level, the risks should be made *as low as reasonably practicable (ALARP)*. This means that when deciding whether or not to implement risk reduction measures, their implementation costs may be taken into account. In this region, the higher the risks, the more it is worth spending to reduce them.

This approach can be interpreted as dividing risks into three tiers, as is illustrated in Figure 2, comprising

- An intolerable region within which risk reduction measures or design changes are considered essential.
- A middle (or ALARP) region where the risk is considered to be tolerable only when it has been made ALARP. This requires risk reduction measures to be implemented if they are reasonably practicable and cost effective.
- A negligible region, within which the risk is generally tolerable, and no risk reduction measures are needed.

In terms of Individual Risk the tiers proposed by the UK HSE are

Maximum tolerable risk for workers	10^{-3} per year
Maximum tolerable risk for members of the public	10^{-4} per year

Negligible risk 10^{-6} per year

Typical acceptance criteria for societal risk and those used in the case study below are illustrated in Figure 3

Mitigation Measures

Once higher risk processes and operations have been identified, risk reduction measures need to be implemented with due concern to applying the ALARP principle described above and to satisfying any legislative requirements. The three key risk reduction measures are elimination, reduction of event frequency and reduction of event consequence. The preferred option is always elimination but this is often not possible when assessing an existing plant, so the alternative options have to be investigated. Possible measures for reduction of consequence may include minimisation of inventory, use of less hazardous materials or reduced process conditions. Possible measures for reduction of event frequency may include use of less corrosive materials, reduction of process pressure or temperature to decrease likelihood of mechanical failure or implementation of an improved safety management system.

The QRA case study below identified a number of areas of high risk. Recommendations were made which were feed back into the QRA model to show the risk reduction they would achieve.

A Case Study - QRA of Kuwait National Petroleum Company

DNV has been working closely with The Kuwait National Petroleum Company (KNPC) on improving the safety performance of their refinery and distribution network. KNPC's processing facilities consist of 3 refineries with a throughput of around 850,000bpd. These are situated on the Arabian Gulf coast around 45km south of Kuwait City. Pipelines carry refined vehicle petroleum to two depots from where it is distributed to 95 KNPC owned petrol

stations and other customers by road tanker. Sea tankers are loaded via facilities a short distance offshore.

A QRA has been performed by DNV using the software, methodology and techniques described above. This included the Mina Abdullah, Shuaiba and Mina Alhamdi Refineries along with a number of unloading and distribution facilities. Individual and societal risk results were produced for the entire QRA, along with individual sets of results for each refinery and unloading facility. Overall risk ranking for each refinery and unloading facility was also calculated. For the purposes of the QRA these were further broken down into distinct units (e.g. crude distillation, hydrogen production, etc.) and risk ranking for each unit was calculated to identify high risk contributors. A set of failure cases was developed to completely describe each unit. Each failure case was defined typically by release material, rate, duration, frequency and location. The KNPC facilities handle a mixture of flammable and toxic materials; the flammables include heavy oil, medium oil products, naphtha, LPG and hydrogen whilst the toxics include hydrogen sulfide, sulfur dioxide and ammonia. Release rates for each failure case are calculated by SAFETI from the given process conditions, leak size and material. SAFETI also determines other source terms including temperature after release, velocity and liquid fraction and droplet size for two-phase cases. SAFETI then calculates the consequence of each failure in terms of dispersion followed by toxic and flammable effects, including the possible consequences associated with fireballs, flash fires, vapour cloud explosions, jet fires and pool fires.

Figure 4 shows the individual risk contours from the whole QRA. From these results and the associated FN curves it was evident that the risks posed by the KNPC refineries exceeded the acceptance criteria illustrated in Figures 2 and 3. Having identified the highest risk contributors as described above, DNV was able to recommend a number of mitigation measures to reduce both individual and societal risk levels. These included an improved safety management system, which forms part of ongoing work at KNPC being undertaken by

DNV Consulting, improved detection and isolation and improved fire protection for LPG tanks. DNV were also able to re-run the QRA model with these measures implemented, to show the effect of the proposed measures. The resulting individual risk contours are shown in Figure 5 for illustration. The initial QRA described above was relatively coarse but DNV and KNPC are now working in partnership on a more detailed QRA which will be used to reduce the overall risks still further.

Figure 1 Classic Risk Analysis Methodology

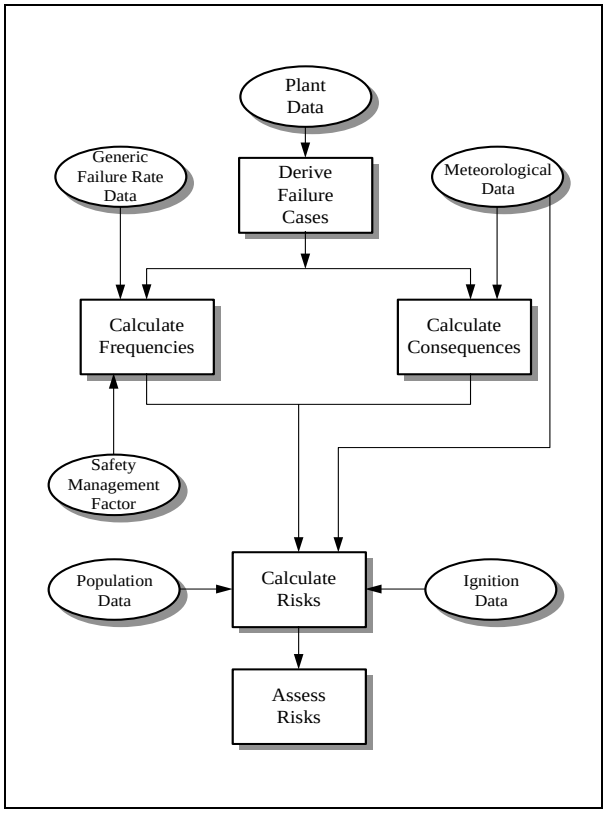

Figure 2 ALARP Framework for Risk Acceptability Criteria

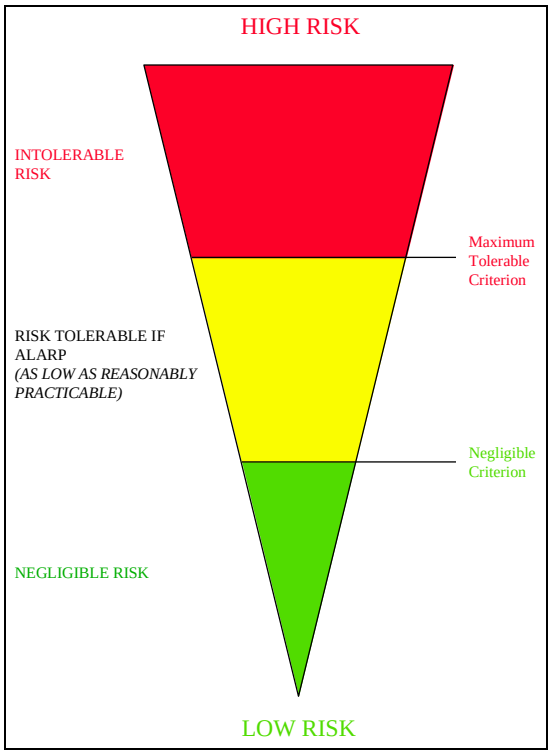

Figure 3 Typical criteria for acceptable Societal Risk

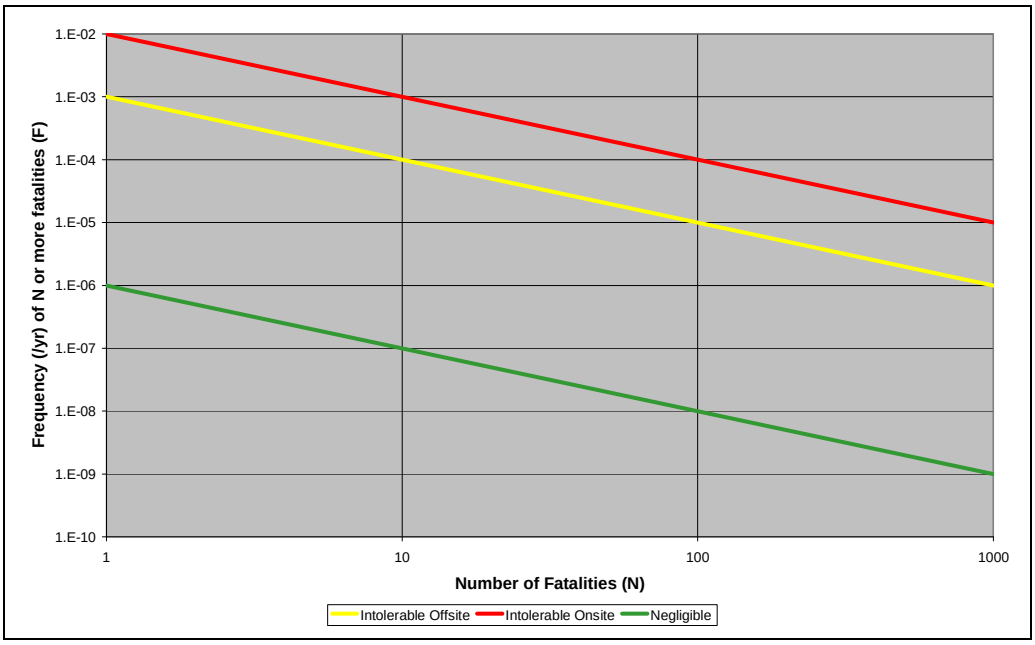

Figure 4 Overall Individual Risk Contours for KNPC Refineries

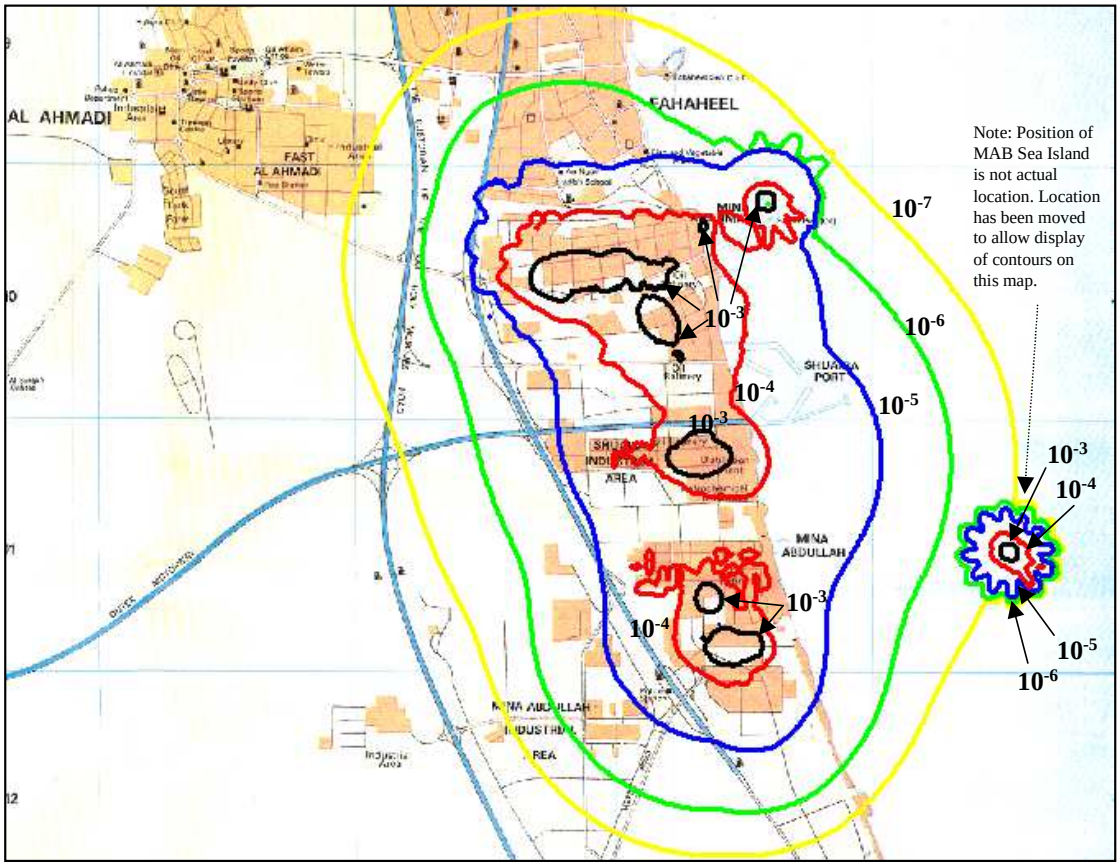
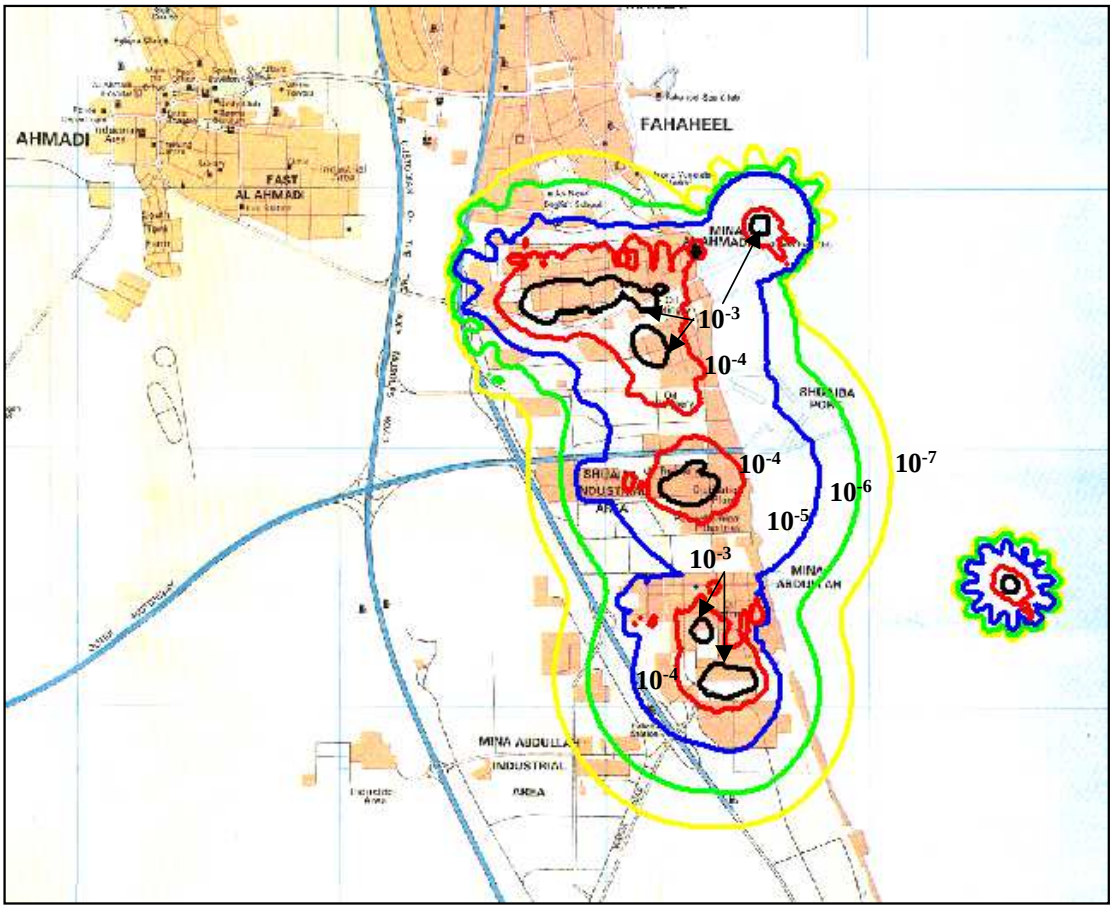
Figure 5 Overall Individual Risk Contours with All Mitigation Measures