QRA – UNLEASHING ITS POWER

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INTRODUCTION

Quantitative Risk Assessment (QRA) has been used since the late 1960s as a tool for regulators, operators and contractors to assess risks posed by installations extracting, processing and/or storing hazardous substances in significant quantities and/or with significant throughputs ("process installations" hereafter). Since the 1980s this has been facilitated by the development of software (starting with Technica's SAFETI – Software for the Assessment of Flammable, Explosion and Toxic Impacts) to carry out the demanding computational elements of QRA, in particular consequence modelling and risk estimation.[1] QRA has become an essential tool in many parts of the world for the development, continued operation and expansion of process installations that meet society's growing expectations of such installations posing as little risk as possible to its members. At the same time, ever increasing pressures to reduce costs without (apparently) compromising safety have required risk reduction to be demonstrably cost effective.

QRA has therefore grown – or rather, been required to grow – from a coarse tool that could be used to assess whether a process installation met regulatory risk criteria to a tool that can be used through most stages of a process installation's lifecycle to demonstrate cost effective risk acceptability and risk minimization. This paper will demonstrate, through history and case studies, how QRA can now meet these sophisticated expectations and how this has been driven by client needs, with software developers responding to these needs.

GROWING EXPECTATIONS

In the energy and process industries, QRA was first developed in the Netherlands, where its original use lay in ensuring that the dykes which protect the low-lying areas from sea ingress were robust enough to withstand all but the worst storm surges. QRA for energy and process industry operations was shown (Slater 1982) to be do-able but to require computer software to be practical.

The initial Dutch risk acceptance criteria divided risks into three bands, with the highest risks being unacceptable and the lowest acceptable as they stood. Risks in the middle band were required to be reduced, not necessarily to lie in the lowest band, but to be demonstrably ALARA (As Low As Reasonably Achievable).

SAFETI, commissioned by the Dutch government and first released in 1982, enabled the risks from process installations to be estimated and assessed to identify where they lay in relation to the criteria. Thus, initially QRA was used as a "go/no-go" assessment tool.

Given the computing power available at the time, SAFETI necessarily had to use relatively simple, phenomenological consequence models in order for QRA studies to be completed within a reasonable time-scale. Use of Computational Fluid Dynamics (CFD) was impractical (and remains so for the bulk of QRA work, as discussed below).

Offshore, the Norwegian Petroleum Directorate (NPD) established a requirement for Concept Safety Evaluations (CSEs) of new installations (NPD 1981), a different approach to QRA but the first formal requirement for QRA offshore. The CSE addressed the risk of impairment of "safety functions" such as escapeways and lifeboats and ensured, early in the design process (before it became prohibitively expensive to make major changes), that the risks were minimized and thus the concept acceptable to the NPD to take forward.

Even from its earliest days, QRA could also be used to assess the relative risks of different concepts for new onshore process installations.

For QRA clients (at that time, the operators of existing process installations), the requirement to demonstrate that risks were ALARP (As Low As Reasonably Practicable) immediately raised the question: what risk reduction measures would be demonstrably effective? This required more than the overall risk levels: it required a breakdown of the risks, by section of the installation and by scenario, to identify the major risk contributors (or "risk drivers"). The SAFETI software developers duly provided the means to do this, although it could not easily be used to identify the particular outcomes (e.g. explosion) that were driving the risk.

In the early stages of a project, the installation layout (onshore or offshore) can be optimized to minimize the risks. Even with details of the process undefined, it became desirable for QRA to be used to identify the highest risk units, so as to guide the installation layout.

Offshore UK, many operators used QRA methods as an integral part of the design process but, prior to the *Piper Alpha* accident of 1988, QRA tended to be applied to specific aspects of the design rather than to assess the overall risks. Consequently, it was mainly used as part of the detailed design when the scope for changes was limited. Examples include the prediction of the risks of ship-platform collision, and modelling of the risks in emergency evacuation. Several operators used the latter to assess and improve their arrangements for evacuation by lifeboat.

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[1] Throughout this paper the term "estimation" has been used in preference to "calculation" as the uncertainties in risk numbers mean that the precision of mathematical or engineering calculations cannot be ascribed to those risk numbers.

In the UK, the HSE developed risk criteria (1988) for the Sizewell B public enquiry, along with the associated rationale. Unlike in the Netherlands and Norway, QRA *per se* was not, and is not, mandatory for ALARP demonstration. The UK also developed land use planning guidelines (Turner & Fairhurst 1989), for developments outside process installations, that were implicitly risk based. Thus QRA was used, not only to assess the risks from a process installation, but also to assess whether proposed external developments could proceed.

The public inquiry into the Piper Alpha disaster (Cullen 1990) identified, amongst many other issues, the importance of blast walls able to withstand a strong explosion. Whilst QRA could be used to estimate the risk from explosions taking into account the blast wall strength, estimating the overpressures that could be generated by an explosion required CFD. These results could then be incorporated in the QRA, and thus was developed a strong link between CFD and QRA, playing to the strengths of each whilst not requiring the power (and resource requirements) of CFD to be deployed throughout the QRA.

The Texas City accident in 2005 placed a new emphasis on the siting of temporary buildings within a process installation (and resulted in a new API standard, RP-753). More generally, risks onsite onshore have increasingly been a concern in the design and operation of process installations. Consequence modelling in QRA software has generally been understood to be valid in the medium to far field but not in the near field. Estimating onsite risk requires models valid in the near field and also requires consideration of buildings' ability to withstand an explosion or fire. Phenomenological explosion models that reflect confinement and congestion on the installation (e.g. through applying the GAME/GAMES metholology: Eggen 1998; Werex et al. 1998) have necessarily become a key part of onshore QRA, replacing more general VCE (Vapour Cloud Explosion) models. CFD can be used too in this context, to inform the QRA rather than as part of the QRA software tool itself. Thus QRA, often in conjunction with CFD, has come to be used to facilitate risk based structural design of process installations (e.g. blast walls, buildings), onshore and offshore, as well as the layout and process design.

The increased expectations of QRA have driven improvements in both modelling and reporting, with the ability to "drill down" and understand in detail the risk drivers a vital feature of QRA software.

All of the above applications have usually and traditionally focused on risk to people. Fatalities of course make news headlines and are extremely damaging to the responsible party's reputation. However, asset damage and loss of production are extremely damaging to the operator's finances: it may take many years to recover to previous production levels. With the means available to estimate the risks of damage to an installation, it is then a short step to present explicit risk estimates for assets and production, as can now be done, for example, by Phast Risk Financial.

What of the environment, especially in the light of BP's Macondo well disaster? QRA can be used to estimate spill quantities and flow rates of hazardous materials into the environment, together with their frequencies. The spill quantities and frequencies can be used to produce an F-S (Frequency-Spill size) curve, equivalent to an F-N (Frequency-Number of fatalities) curve for personnel risk, but equivalent criteria do not appear to exist. Furthermore, spill quantity is not equivalent to number of fatalities as it does not measure the impact on the environment (e.g. fish, trees). Models exist for environmental impact; however, true environmental QRA is beyond the scope of this paper.

QRA FOR (THE PROCESS INSTALLATION'S) LIFE

Today, QRA is no longer seen as an isolated activity but as an integral part of an overall risk management strategy throughout an installation's life, including modification and expansion.[2] At different stages, it can provide different inputs that can, properly used, ensure that a process installation's risks are minimized cost-effectively. Whilst these will almost invariably not be the only considerations as design choices are narrowed down, no company can afford to proceed without sufficient regard to the safety risks as a major accident will severely impact their reputation, cash flow and share price, possibly even their survival.

Figure 1 shows how QRA and CFD can be applied from concept through to operation and then modification or expansion. How the QRA is carried out and what use can be made of the results changes through the various lifecycle stages. CFD can be, and increasingly is, used to inform the QRA and so make credible the results obtained from the phenomenological models used in the QRA, as will be shown in Section 4.0.

The only stage where the application of QRA is restricted is decommissioning and dismantling. However, at this stage the installation is expected to be empty of hazardous process substances and the safety issues are largely similar to those faced in any major dismantling project, being largely structural, mechanical and electrical rather than process; they shift away from major hazard and occupational safety to occupational safety only.[3]

CASE STUDIES

The following are case studies derived from real-life projects that illustrate the different benefits of a QRA over a process installation's lifecycle.

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[2] In this context, QRA is not seen as sufficient to demonstrate that the risks of a process installation's operation are acceptable: the importance of safety management has been increasingly recognized and accordingly, at least in the UK, a Safety Case must demonstrate adequate safety management, not only adequate design. However, QRA is not superseded; rather it forms a valuable part of the whole process of ALARP demonstration.

[3] However, many accidents have occurred because plants were shut down with chemicals left in them and not dismantled until years later by which time everyone had forgotten what was in the plant.

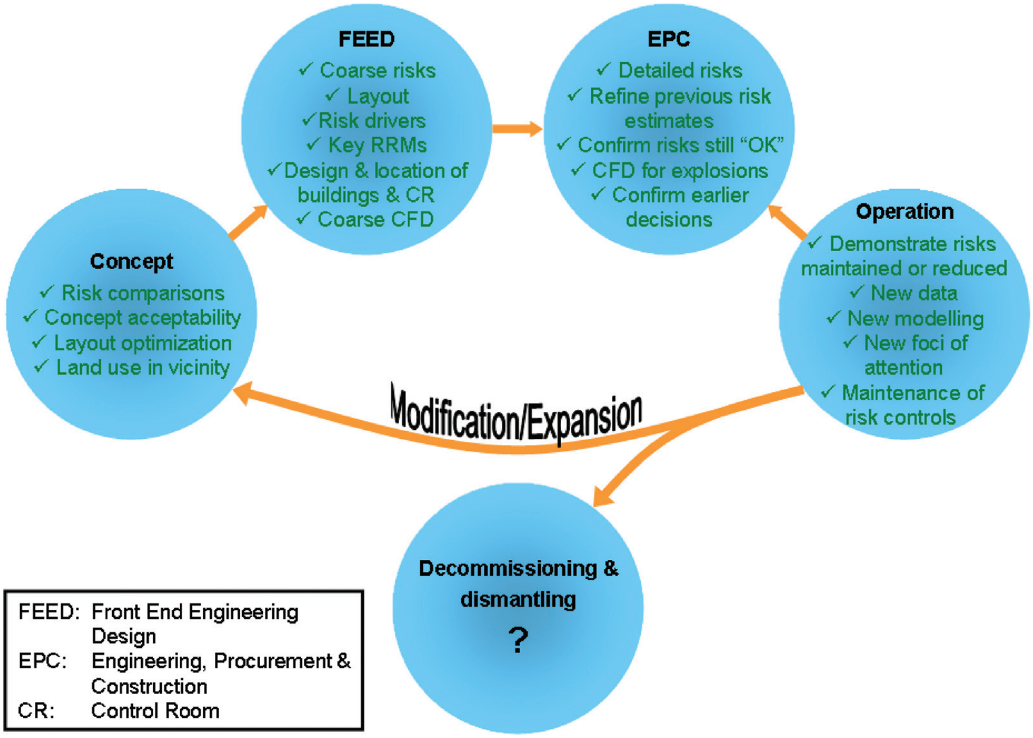

Figure 1. QRA during the installation lifecycle

CONCEPT STAGE

The first case study relates to the conceptual design of a petrochemicals complex which was to be sited in an area bounded by busy motorways. Only the process units and their throughputs were known at this stage. There were plans in place to expand the petrochemicals complex in the future to a number of potential sites across these motorways. A high-level QRA was conducted with the following key objectives:

- To identify and assess hazards related to the facilities.
- To obtain preliminary estimates of the onsite and offsite risk levels related to the facilities, and assess these against the local authority's land use planning risk acceptance criteria.
- To validate the current site plan, regarding the relative locations of the various units.
- To highlight the risk "hot-spots" in the plant and thereby help to focus controls where they matter the most.
- To recommend preliminary risk reducing measures to ensure that all risks are ALARP so far as can be achieved at this stage.

The QRA, apart from achieving the above objectives, identified the need to modify the original site layout in order to minimise offsite risks. The QRA was employed in revising the site layout: new locations were recommended for a number of process units, minimum separation distances were proposed for the different facilities making up the complex and a number of potential sites for future expansion where identified as being unsuitable for their intended use. Toxic hazards were identified as dominating offsite risks and it was recommended to focus particular attention on these as the project developed. Thus, despite the lack of information (e.g. plot plans, PFDs, heat and material balance) to be able to carry out a "classic" process QRA, it was possible to carry out a coarse QRA that could provide meaningful input and recommendations to the design process.

Another case study relates to the conceptual stage of a major offshore hydrocarbon production project. A key element of this was the evaluation (in terms of risks to people) of two concept options for the offshore facilities:

- Option 1: a semi-submersible platform processing gas and an FPSO (Floating Production, Storage and Offloading) for condensate processing and storage.
- Option 2: gas and condensate processing on several bridge-linked platforms with an FSO (Floating Storage and Offloading) for condensate storage.

A high-level QRA was carried out using the same risk model for both concepts and using a common set of assumptions. The study's principal objective was to provide a clear comparison of the risks to personnel for the two concept options. Other specific objectives included:

- Providing recommendations to ensure that risks to personnel, the environment, and the asset, as a consequence

of hazardous events are reduced to a level that is As Low As Reasonably Practicable (ALARP).
- Identifying the particular hazards, systems or equipment, which have major significance for the presence or control of risks.
- Demonstrating clearly the effects of the uncertainty of data used in the risk model, where assumptions have a significant impact on the risk levels, and providing references for all data used in the analysis.

The QRA achieved the above objectives in spite of the coarseness of the design data available at this early stage of the project. The uncertainty and conservatism was recognized, however the risk indicators enabled a clear comparison of the risk levels associated with both concepts. The risk levels were not the only factor influencing the concept choice; the economic factor was also an important consideration but was outside the scope of the QRA study.

A follow-up QRA study associated with the selected concept option (Option 1 above) aimed to compare various layout options for both the semi-submersible platform and the FPSO vessel, to ensure the layout design was optimized. The QRA model was used to evaluate the variation and the magnitude of variations between the various layout options. This took into account variations in terms of location of equipment, blast/fire walls, and dimensions of the decks.

FRONT END ENGINEERING DESIGN (FEED) STAGE

The third case study relates to the FEED stage design of an LNG/LPG facility consisting of multiple LNG production trains. A conceptual QRA had been conducted earlier; however, due to the limited project specific information at the concept stage, the QRA could not provide the preliminary risk-based design information required at the FEED stage. As such, the concept stage QRA was revised with the following key objectives:

- To quantify the risks associated with the project facilities and operations.
- To check or redefine safety distances to permanently occupied buildings and temporary camp facilities, as well as the level of fire/blast rating required for all buildings (occupied and unoccupied).
- To assess the acceptability of the quantified risks, to identify the risk drivers, and to propose potential measures for risk reduction.
- To assess the effectiveness of safety systems.
- To assess Simultaneous Operations (SIMOPS) risks to construction workers as the facility develops.
- To define ignition source exclusion zones at the LNG/LPG berths satisfying a risk-based design criteria.
- To size LNG impoundment basins satisfying a risk-based design criteria.
- To define passive fire protection requirements around the LNG trains satisfying a risk-based design criteria.

Exceedance curves obtained from the QRA were used to define:

- Appropriate fire and blast design loading to buildings and safety critical elements.
- Optimum (risk-based) sizes for LNG impoundment basins.
- Exclusion zones around the LNG/LPG berths.
- Maximum heights for the application of passive fire protection over the entire length of the LNG trains, satisfying a set of risk criteria.

An example of an exceedance curve is provided in Figure 2. Furthermore, the results of the QRA, as illustrated in Figure 3 (overpressure frequency contours), enabled the determination of appropriate safety distances for the siting of temporary occupied (construction) facilities during SIMOPS.

ENGINEERING, PROCUREMENT AND CONSTRUCTION (EPC) STAGE

This case study relates to the detailed engineering design and construction stages of a gas compressor facility. A QRA was required with the following objectives:

- To quantify the risks associated with the project facilities and operations.
- To assess the associated risks to assets, loss of production and the environment.
- To assess the acceptability of the quantified risks, to identify the risk drivers and to propose potential measures for risk reduction as the detailed design progresses.
- To assist in demonstrating that the risks are ALARP.
- To assess the effectiveness of safety systems.
- To check or redefine safety distances, fire zoning, fireproofing, fire and gas detector arrangements.
- To perform Safety Critical Element analysis and develop performance standards for each.
- To perform escape and evacuation analysis and propose the number and location of muster points to aid in developing escape routing plans.

The above objectives were largely met by using a combination of the various risk reporting capabilities (exceedance curves, hazard frequency/risk contour maps, risk ranking reports etc) available within the DNV BLAST (and now Phast Risk 6.6) software tool (see Figures 2 and 3 for example).

OPERATION AND MODIFICATION

QRA can provide vital support during the operation of a process installation, both to support changes to the installation and in the light of new knowledge or data. This is illustrated by a series of studies for one offshore operator with an asset comprising 18 installations:

- For one platform, high overpressures had previously been predicted by the FLACs CFD model prior to JIP

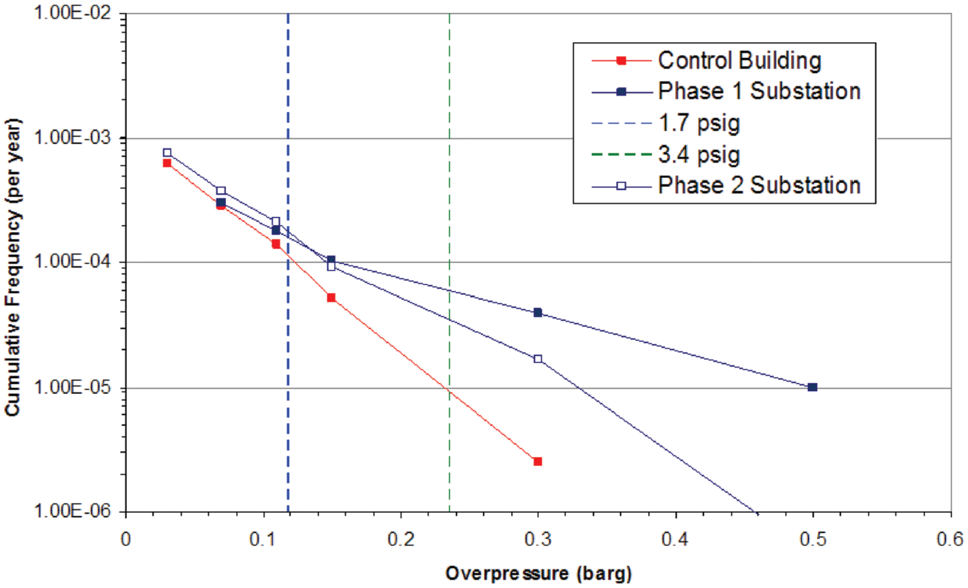

Figure 2. Example (peak side-on) overpressure frequency exceedance curve

experiments. Following these experiments, the operator sought an update of the explosion results. DNV applied Norway's NORSOK method. The project aroused very high interest from the UK HSE. Also, over a period of six years a number of remedial measures had been put in place to reduce potential overpressures: holes in the deck, gas curtains, inventory reduction, new valves to isolate inventories from other decks etc. In the light of the changes and the knowledge acquired from the JIP, it was decided to re-analyse the explosion risks completely.

- A series of proposed modifications were investigated using QRA to enable the operator to demonstrate to the HSE that the risks would remain ALARP. These included:
  - Two new wellhead platforms (NUIs: Normally Unattended Installations)
  - Several tiebacks of new subsea facilities to existing installations
  - Reinstatement of an abandoned well
  - Firefighting facilities on NUIs
  - Installation of methanol tanks and injection skid on 2 NUIs
- An increased emphasis on LOPA (Layers Of Protection Analysis) by the HSE and the operator, with the concomitant potential for a mismatch between consequences analysed in the QRA and qualitative judgments on consequences in the LOPA, led to the operator requiring additional outputs from the QRA that could be used in LOPA to ensure consistency between the two.

EXPANSION OF EXISTING FACILITIES

The final case study relates to a refinery expansion project involving the construction of 22 new process units as well as 8 new utility units. A QRA was required with the following objectives:

- To quantify the risks associated with the expansion Project facilities and in relation to the existing refinery facilities.
- To assess the risks against relevant local risk acceptance criteria.
- To assess the potential for escalation/asset damage/domino effects within units comprising the expansion project facilities and as it relates to the existing facilities.
- To recommend risk reduction measures to ensure that all risks are ALARP.

The QRA identified that, accounting for risks from the new refinery alone, the new (expansion project) control room building would need to be designed to about 120 mbarg; however, considering the additional risks from the existing refinery, the control building will need to be designed to 220 mbarg. The insight provided by the QRA was particularly useful in preventing underestimates in the blast load design rating applied to the new control room building and illustrates the danger in overlooking the contributions from existing facilities to neighbouring new-builds.

THE RECURRING THEME

The recurring theme in many of the studies described above is the challenge of modelling the risk from explosions. Obtaining realistic estimates of overpressures and incorporating these estimates in the QRA within an acceptable timescale and budget is increasingly required. If the overpressures are under-estimated, then an accident could result in far greater damage and casualties than anticipated.

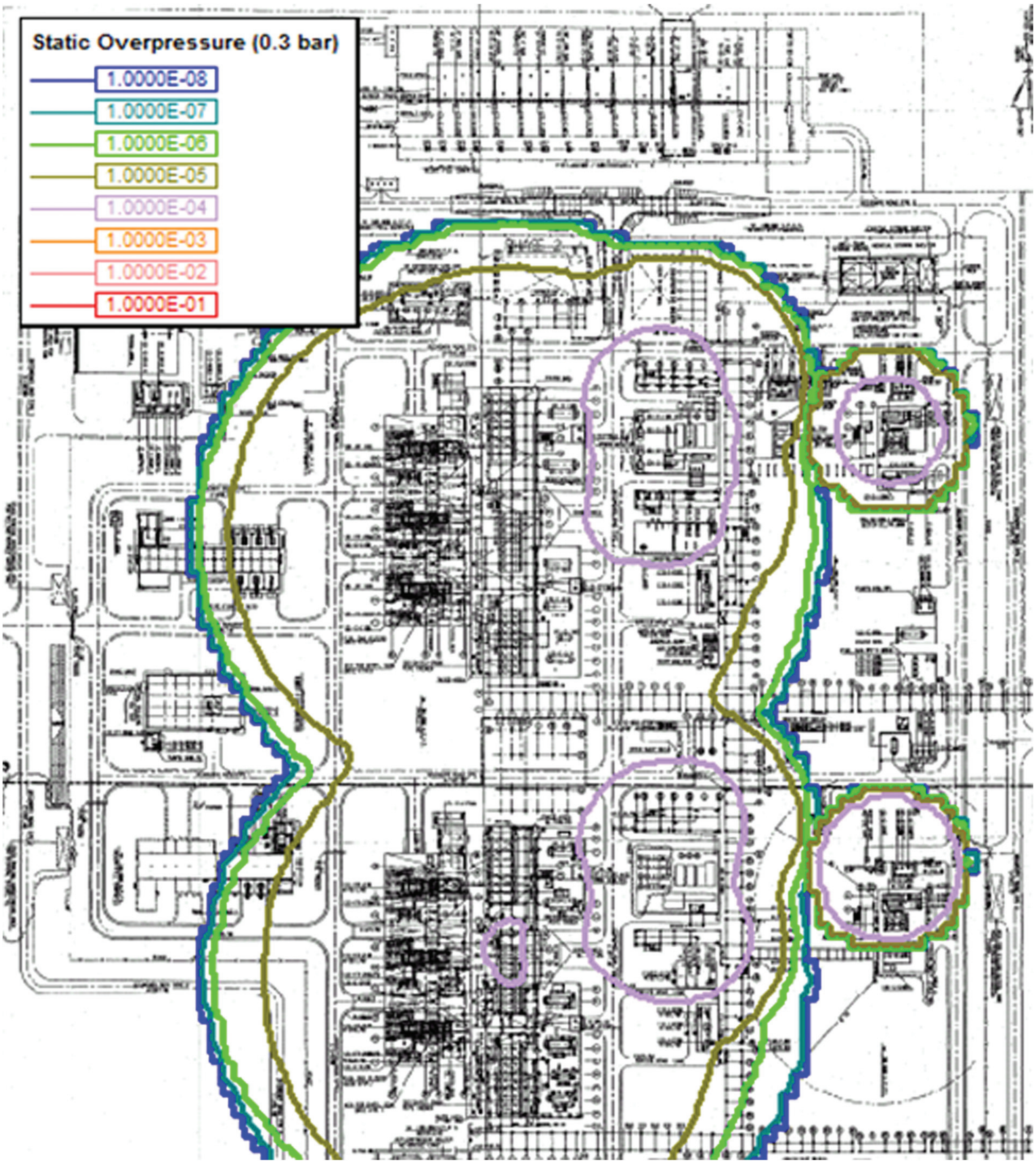

Figure 3. Example 0.3 barg (peak side-on) overpressure (hazard) frequency contours

However, overdesign (i.e. using over-estimates of overpressure) is invariably costly even if practical and may be far from cost-effective.

With many (typically hundreds of) loss of containment scenarios to analyse, computing power and QRA analysts' knowledge currently preclude extensive use of CFD; instead, CFD has to be applied to selected scenarios and the results generalized to apply throughout the QRA. This has been accepted practice for many years in offshore QRA, where ensuring adequate but cost-effective protection against explosions has been vitally important. Onshore, simple phenomenological models were used for many years, however they are not fit for purpose when input to design decisions is required.

The well-known Multi Energy and Baker Strehlow models provide a considerable advance to bridge this gap. Until recently, they weren't available in general purpose QRA software, although they formed the basis of DNV's in-house tool BLAST; they are now available in DNV's commercial Phast Risk 6.6, enabling their routine use in QRA for all the scenarios modelled.

CFD remains a tool for use by specialists but it is increasingly used as an adjunct to onshore QRA, to enable the inputs to the QRA's inbuilt phenomenological models to be tuned. This increases confidence in the realism of the QRA results, giving greater confidence for major investment decisions.

FUTURE DIRECTIONS FOR QRA

- QRAs are increasingly being looked upon as sources of asset/process design information. QRA tools will therefore need to be constantly updated to adapt to the growing list of requirements.
- Detailed QRA results can be used, and are increasingly being used, to identify the key process safety technical controls; this in turn can be used to ensure these controls are maintained and to show how, if they become degraded, the risks will materially increase.
- Environmental risks are only crudely modelled by current process QRA models. As increased attention is paid to these, the scope of QRA models will need to be extended in order to address them. Environmental risk acceptance criteria will also be required.
- QRA tools are generally either suited for onshore or offshore risk assessments. With the increasing computing capabilities now available to users, single tools supporting both onshore and offshore risk modelling requirements are likely to emerge (e.g. DNV's Phast 7 project).
- Most QRA tools employ phenomenological models, and in some cases, look-up functions based on outputs from CFD studies. With the ongoing advances in computing, QRA software tools are in future likely to fully support CFD based deterministic modelling in addition to existing phenomenological modelling.
- In the meantime, there is increased interest in employing CFD models to tune phenomenological models (e.g. the GAMES project and the recent updates to the Baker-Strehlow explosion model). It is likely that this trend will continue while QRA tools with full CFD capabilities are being developed.

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