Assessing the Risks When Expanding Process Plants or Building New Units on Compact Sites

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Many Energy, Process and Utility Plants are being expanded or new units are being added to sites which often leads to existing facilities being compromised. This paper will provide some insight into how the plant risk assessment should include a review of the exposures to infrastructure, the original plants, and utilities.

A number of examples will be given in Case Studies to show why the layout needs to undergo a thorough risk assessment before inserting new facilities and changes may have to be made to ensure the integrity of all of the site.

The reason for this paper is to highlight areas of new projects which are often overlooked by the owners or the contractors as they concentrate on the new design engineering and construction.

The paper will also address revamps where increased production is the ultimate goal again using some or all of the existing plant equipment.

One of the main findings during my work as a risk consultant for the past 30 years worldwide and former plant designer is that layout or arrangement has become as important as verifying the process calculations.

Projects which require to be executed inside 'live boundaries' will also be discussed with guidelines on how to mitigate the risk exposure.

Solutions which have been generated to counteract increased risk levels and protect workers as well as the site will be detailed.

Failures will include details on projects which have suffered losses due to inadequate hazard analysis and subsequent risk analysis.

Key words: Revamps; Risk Assessment; Congestion; Live Sites

Design of Brownfield Sites

Large energy, chemical, oil, gas, petrochemical, and refineries are rarely designed as a final configuration. There are a variety of reasons for this:

1) The investment profile is insufficient to construct all the plants in one phase and production may be required to provide funds for expansion.
2) Sales markets change over time with new demands for different products or increased capacity of existing facilities.
3) Environmental Legislation demands emission control is upgraded with improved contaminant removal such as toxic gases, water treatment and waste disposal.
4) More efficient modernized units are required to eventually displace older plant, and these have to be built before decommissioning. This might include process, utilities, storage and pipelines.

Most plants are built in a designated area which is either owned by the company or allocated by Governmental Authorities. This may limit the footprint area available for expansion and can result in new facilities being sited close-by existing plant. All companies generally follow the spacing guidelines (API, NFPA and so on)[1][2] and some have their own in-house standards. Across the world the siting of new process units or utility systems is generally carefully planned by carrying out the following actions: -

1) A risk assessment of the hazards presented by the new facilities to and from the existing plants. Such risk assessments include modelling loss of containment of significant volatile materials which could lead to major fires and/or explosions, toxic gas drift, high pressure vessel rupture, BLEVE, fireballs, and so on. There are many software programmes available to undertake the analyses[3]. The main weakness in these is that they are less reliable as the congestion of the site footprint is increased. The key is to prevent increased confinement where release of flammable substances may occur and provision for access of the emergency services and proper emergency escape routes for on-site personnel. Above all a major factor of plant layout must be to prevent a 'domino' loss scenario occurring, ensure safety within on-site occupied buildings and control access of unauthorised personnel.
2) Checking the orientation of any new plant with respect to the site undergoing the expansion with respect to wind direction and also equipment positioning at its boundary. For example, vessels which could BLEVE should not be end on facing existing plant, spheres should not be positioned directly adjacent to a process or utility unit particularly when the unit has fired heaters, rotating machinery, or itself contains large, enclosed inventories of flammable materials[4].
3) Verifying that the Control Room or slave relay rooms are not compromised. This will depend on the specification of the existing facilities with respect to blast resistance, any potential liquid draining towards their location or any gas release which could reach the location.

4) Ensuring that critical utilities plant is not subject to damage.
5) Maintaining adequate firebreaks in all areas.
6) Noting any toxic materials that may be brought close to existing plants and therefore personnel (e.g., siting of an HF Alkylation unit should be carefully reviewed). The need to locate hazardous materials facilities as far as possible from site boundaries and people living in the local neighbourhood. The need for plant operability and maintainability[(24)]. In determining plant layout designers should consider whether a hazard can be eliminated altogether; whether the inventory of hazardous substances can be reduced/substituted, or the process operating conditions can be changed to less severe values (temperature, pressure, concentration).
7) Checking that pipelines which are run in racks are not compromised (this may be feed or export lines which were originally out of risk exposure contours).
8) Plant layout is often a compromise between a number of factors such as the need to keep distances for transfer of materials between plant/storage units to a minimum to reduce piping run costs and the geographical limitations of the site. Lump Sum Turnkey Projects are nearly always based on tight plot areas and arrangement of the components to meet all spacing guidelines is a challenge[(4)].
9) Use of the existing site roadways, drainage and utilities routings; these facilities were originally designed for a purpose.

Front End Engineering Design (FEED)

Once the preliminary layout has been set in the allocated footprint area, the FEED can be commenced:

1) The best method of carrying out a revamp or adding plants to an existing site is to prepare a full engineering package which scopes the work entirely. This may be carried out by the engineering group of a licensor or by a reputable contractor. This should be a complete document including: -
   a. Project Description with Process and Utility Flow Diagrams including material and heat balances.
   b. Design Basis (all metrological data), local land topology, exposure to natural perils (earthquake, tsunami, cyclone, hurricane, flooding, lightning and so on).
   c. Soils report illustrating all piling requirements – reclaimed land needs special attention.
   d. Revised Plot Plans showing clearly new and modified areas.
   e. Revised Piping and Instrumentation Diagrams showing all additions/changes (clouded) and deletions (hatched out).
   f. General Arrangement of all the new piping highlighting all connections into the existing pipework, pipelines, or equipment with a proposed timeline for implementation. All new/modified Isometrics.
   g. Complete list of tagged items and their details (Design Pressure/Temperature, Material of Construction, Internals).
   h. Revised Electrical Single Line Diagrams, Hazardous Area Classification Drawings.
   i. Structural Reports on New Loads for all modified areas.
   j. Level 1 to 4 work schedules per week/month including Long Lead Items and Critical Path Analysis.
   k. All changes to the control systems (loop diagrams, modernisation upgrades).
   l. Interface documents for piping, power and instrumentation, HVAC, LOTO (Lock Out-Tag Out system to be used) – these are critical.
   m. A full list of all blinds (isolation of any live processes), double block and bleeds, locked open or closed valves should be available.
   n. Spares Requirements (both commissioning and 2-years operational).

In addition, the following should be prepared (either by the owner or contractor): -

2) A full list of all major inventories in the plant, how they can be isolated (emergency shutdown valve, manual valve). The inventory type should be identified and operating conditions (pressure and temperature).
3) A document describing the work permit system to be used during the revamp or new plant suitable for contractor training.
4) Implementation of the site's Process Safety Management System to the project including use of Hazard Analysis, Management of Change Procedure, Healthy and Safety Cards, Near Miss Register, Safety Audit Procedure, Working at Height Training, Security Requirements for site access, Evacuation, Muster points, Alarm Recognition.
5) Firefighting requirements for the existing site and in the new construction, fire-watch, area fire pre-plans, revised fire zones drawings.
6) Camps, Catering Plans, Transport and ID card access system. Note: expansion or revamp manpower is often under-estimated.
7) Temporary Buildings required – losses have resulted from poor siting of temporary structures.
8) Training Programmes for staff and contractors.
9) Disciplinary Procedures.
10) Confined Space Entry, System Inerting (blanketing).
11) Welder Qualification, Inspector Levels per area.

Assumptions which need to be confirmed by the owner: -

1) All existing plant documents are fully up to date – this is critical. Do not attempt to revamp/expand a facility unless these are current.

2) All documents for the current site are available electronically and hard copy.
3) Existing Flare, Vent, Blowdown, Drainage has been checked for capability – again the documents must be current.
4) All other Utilities that will be re-deployed such as air supplies, water, heating/cooling medium, and so on.
5) All Environmental Permits have been approved and Impact Statements have been produced.
6) All plant clamps, repairs, deficiencies have been identified (ready for elimination).
7) Condition survey of all existing systems with full details of deficiencies such as corrosion, wear and tear, bypassed/faulty instrumentation.
8) Whether existing pipe racks, cable trays, supports can take the expansion loads without overheating, overweight loads, access problems. If it is too difficult to install new pipework or cabling, then new racks should be installed (electrical above pipe racks). Cable pulling is very problematic in near full racks.
9) Conduct a vulnerability analysis to checks whether: -
   a. Increased fire/explosion risk has been generated (additional cabling or piping which is now installed close to or directly over existing systems).
   b. Whether the existing fire protection systems will perform in a more congested area or need to be supplemented.
   c. Access from all directions is still possible for maintenance/operation/firefighting.
   d. Whether ventilation systems (in switch rooms, control rooms, substations, warehouses) are still capable of their design duties. For some reason the installed electronics often has a tight temperature sensitivity.

Further work: -

1) All new and modified systems to undergo a complete HAZOP which should preferably be conducted by a third party.
2) QRA of the Plant including the completed new project (best carried out by a third-party consultant).
3) Pre-Start-up Safety Review (PSSR) document.
4) Punchlist of corrective work for Contractor.
5) Positive Material Identification, Storage of Deliveries, Quarantine Areas for items with incorrect paperwork or suspect materials, return of rejected equipment/materials. Look for damage on delivery.
6) Testing and Commissioning Programme.
7) Clean-up on site at all times of implementation.

Lessons Learned: -

a) A clear unambiguous scope is required together with a Contract which covers handling of any Variances.
b) The cost estimate accuracy needs to be within the agreed budget and have a sound basis.
c) Assignment of Experienced Qualified Staff to the Project (both for the contractor and also the owner). An eye for detail is mandatory.
d) The Control System design needs to be handled by a dedicated team of instrumentation engineers from start to finish without over-embellishing (and adding too many alarms). If possible, members of the operational/maintenance team should include the designers (or be trained to problem solve). A critical point for a successful project.

Review of Final Options

Before any project may begin Detailed Design, any options developed by the licensor/contractor should be studied and the final selection presented to the Board/Owners for their decision (with any Cost Benefit Analysis).

The agreed project scope is commenced with the selected contractors and vendors (after any tenders have been processed). Long lead items are identified by the Procurement Group and these orders placed first.

Involvement of Owner's Disciplines

All disciplines should be able to review the design at an early stage and throughout: -

a) Process, Mechanical, Electrical. HVAC, Instrumentation Engineers to run checks on the design and approve documents.
b) Operations – continuous input with particularly involvement on control/monitoring/shutdown instrumentation and the production/approval of Operational Procedures.
c) Maintenance – plant accessibility for all routine and turnaround maintenance activities. The production/approval of Maintenance Procedures.
d) Inspection – materials selection, positive material identification, vendor works' inspection and collection of all thickness measurements for equipment/pipework as they are completed to provide baseline data for future trending in the coming years. Inspection will load this into their monitoring system.
e) HSE – continuous involvement in the design and site activities, establishing the effectiveness of permits, incident reporting, fire protection systems, corrective measures.
f) Security – ensuring sites are secure from theft, any form of malicious damage, worker identification, approval to access key areas. The main areas of concern are found to be portable units such as welding equipment and high value parts.
g) Human Resources – recruitment, training, behavioural assessment, disciplinary matters.
h) Procurement – required to identify long lead items and ensure their delivery meets the intended project schedule. Particularly attention to ordering of bulk materials in correct quantities. All equipment is then ordered as the design is completed (usually tagged items such as vessels, tower, drums, pumps, compressors, turbines, motors furnaces, exchangers, transformers, switch gear) and then all bulk materials such as piping, instrumentation, fittings, valves, cabling after Material Take Off has been carried out – revisions may be necessary as the design is firmed up. Deliveries must be stored under manufacturers' instructions until they are to be installed in the site.

i) Construction - there may be modifications to existing equipment and systems, and these have to be planned and carried out under Management of Change Procedures. Tie-ins, replacement of nozzles and post weld heat treatment, in particular, need to be controlled under permits.
j) Punch-lists will be cleared.
k) The Testing and Commissioning Team ensures Manufacturers' input and assistance with alignment of rotating equipment as necessary prior to any mechanical completion phase. This could be staggered as areas are completed and the plant is made ready for hydrostatic or pneumatic pressure testing. In most cases a 72-hour performance test will be run at capacity. The plant will then be ready for Operations and all areas signed off as accepted. Operations will then control the plant.

Problem Areas

1) Inadequate budget set due to a poor cost estimate is a very common problem.
2) Late project changes impacting the schedule = are they really necessary ?
3) Sufficient man-hours and project duration must be allocated for a successful project which should be controlled by detailed planning and schedules and achievement of realistic milestones. Revamps usually require additional design/construction man-hours compared to new builds (20-50% higher per million invested).
4) Over-complicated approval cycles – the contractor is responsible for executing the contract and Lump Sum Turnkey Contracts have a direct effect on contractor profit.
5) Use of non-reputable suppliers for the equipment and materials. Quality Control is paramount.

Lessons Learned

1) The contract is 'king' and is the only legally binding document.
2) Poor Block Valve selection (early failure through inadequate materials or robustness).
3) Innovation (new types of equipment, items) should be avoided in revamps/expansions due to their effect on schedule.
4) Poor steels quality, unsatisfactory weld heat treatment processes.
5) Ignoring corrosion concerns.

The next section of this paper describes some of the problems arising from expansion projects

Case Study No.1 - New Downstream Units

In order to illustrate the intent of this paper – consider the case that Company ABC Limited constructs an ethylene cracker in a green field site which then supplies downstream polymers units. After 6 years there is a demand for Acrylates to be produced and two new phased plants will be constructed. Products from the cracker are directly pumped to these new units either from the cracker itself or its storage.

Thus, the new units would be built adjacent to the cracker to reduce the cost of piping, perhaps share the utilities, firewater system and so on. The land area will be allocated, and the company carries out a risk assessment to instigate the impact of an incident arising from the cracker or the new Acrylate units. This will check the boundary spacing criteria. However, although there are numerous calculations which can be carried out for loss of containment from all the significant hydrocarbon inventories present in vessels on both sets of plants, there are other important assessments to be made.

Cracker layouts are usually standardised by licensors which gives the overall unit layout of the furnaces, hot, cold sections and so on and this is similar for specialist chemicals where the plant often has 'an off the shelf layout'.

The illustration below shows how an explosion model(3) is used to predict potential a VCE (vapour cloud explosion).

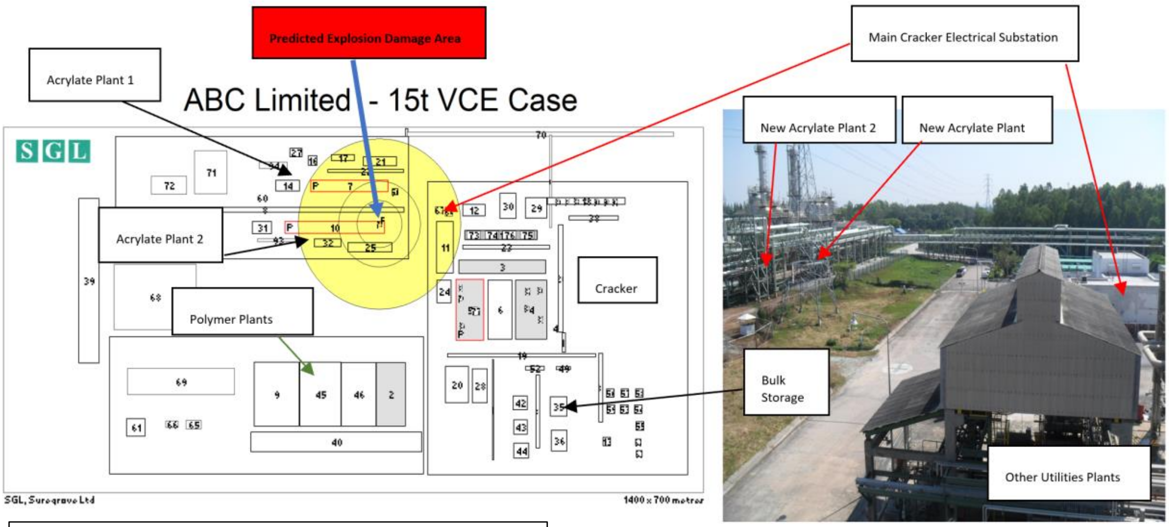


Figure 1 – Explosion on New Plants impacts Cracker

Problem Areas

Consider how the remaining site layout has been arranged: -

1) The power for this particular cracker is supplied from the national grid and originally the main electrical substation was positioned at the edge of the plot away from the main cracker plant inventories and upstream of the furnaces which was a good design feature. Now it is compromised by the new plants being very close with some large hydrocarbon vessels processing C4s. A relatively low-grade explosion or VCE could knock out all of the transformers and shut down the cracker as well as the downstream units, and the feedstock to downstream polymer units. The solution could be to move this substation, protect it, split the system into 2 locations and various ideas were forthcoming – including building an earthen bank in front of the substation thereby hiding it from any potential blast wave.
2) The Firewater system was originally designed to be connected to an onsite pond adjacent to part of the ethylene plant – an additional fire pump was required to meet new expansion design loads. The solution was to locate the new pump and a major water supply away from the cracker site – this was necessary to provide the increased demand, upgrade the firewater storage and provide protection on all of the units irrespective of the events which might occur.
3) As part of this review there was a study on new pipe racks supplying feedstocks and products which were to be run along the boundary of the plants (to supply a second cracker under construction on another site). It was concluded that a worst-case scenario within these sites should not impact on the pipelines except for shrapnel which would most likely require a local repair.

Lessons Learned

1) A loss incident originating from the new plants could knock-out critical utility systems (such as power) and result in a major production outage from the cracker which feeds all downstream units. Cross exposures should be studied.

Case Study No.2 – New Pressurised Hydrocarbon Storage

This was a review of 6 new Horton spheres which were located directly adjacent to the process area (to minimise piping runs and therefore reduce materials, inspection/maintenance costs) to increase storage capacity for the products following a cracker revamp.

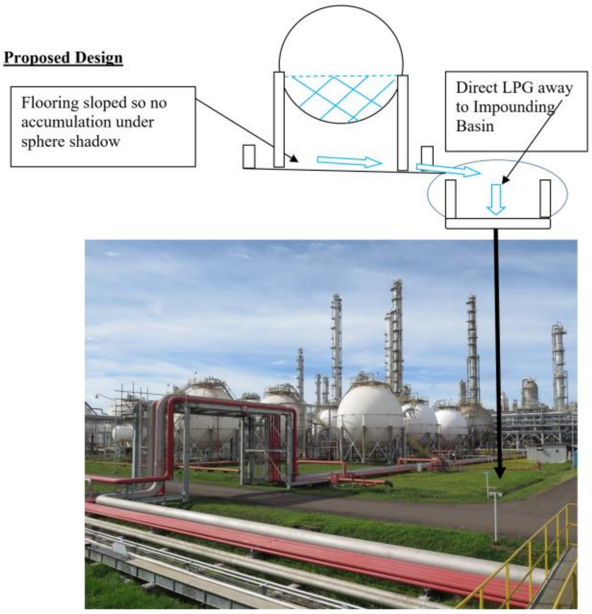


Figure 2 – Pressurised Storage Near Process Plant

Problem Areas

The spheres' plot area is flat, and any leakage will not drain away from underneath the sphere shadows thus presenting a BLEVE exposure which could also impact the process areas. Locating storage close-by process units probably increases the risk exposure by a factor of at least 10-fold.

The solution was to provide an impounding pit which could hold part of the contents of a sphere (after a flash calculation was included) and is reached by an open drainage trench sloped from the sphere bund [(1)(2)]. The area under each sphere was also sloped to prevent the loss of containment pooling and resulting a fire case directly impinging on the sphere surface. Also, a review of leakage points included elimination of some small nozzles on the bottom of the sphere and replacing all the bottom connected lines with fully welded piping, installing EIVs outside the sphere shadow and increasing the firewater deluge rates by new sprinkler rings and deflector plates.

Lessons Learned

1) BLEVE risks must always be avoided not only for pressurised storage but also for vessels in the process areas.
2) Design of systems such as sampling points, drainage connections and other fittings in the liquid phase should be avoided/eliminated and all welded piping used wherever possible.
3) Running a firewater wettage test will reveal whether the entire sphere surface is covered by firewater.

Case Study No.3 – Field Compressor Station

This project involved the installation of a large compressor and trunkline for sour gas re-injection into an onshore oil and gas field. The gas is concentrated before re-injection and has a high Hydrogen Sulphide content.

Figure 3 – Use of Gas Barrier during Expansion

Problem Areas

The gas compression system has to remain in operation as it re-injects sour gas to maintain the field reservoir pressure and production.

The construction workforce on the expansion could be at risk from a sour gas leak from the existing facilities.

A risk assessment was carried to investigate whether a barrier was required to be located between the existing compression and treatment facilities and the new construction to protect the workforce. Although the hydrogen sulphide could still be released from the existing facilities the barrier (essentially a high wall) will direct any gas release in a perpendicular direction away from the new construction. A row of gas detectors provides warning of a release of gas so the workforce (equipped with their own gas masks and air cylinders) can take immediate action.

Lessons Learned

1) This type of protection is only suitable for plants which are located in uncongested flat plots (with no surrounding hills) such as onshore oil and gas developments.
2) One of the most important facts to be taken into account is the location of any plant processing toxic materials. It may be an obvious statement, but such plants should never be positioned close to populated areas (towns or cities) and relocation of the public away to a safe location should be a prime consideration.

Case Study No.4 - Control Room Protection

The position of the Control Room is critical to the safety of personnel and the plant itself. It provides the following duties which cannot be compromised under any circumstances: -

1) A safe haven for any person on the site in an emergency situation such as toxic gas release, some plant fire cases (which are unlikely to engulf the entire facility) and severe weather occurrences.
2) The initial siting of the control room should be peripheral to the process areas and not in the centre. In some cases, the Control Building does not have to be blast resistant, but it must be realised that any plant expansion may impact a future risk analysis.
3) It is good practice to use a self-closing door, gas detection in air intake ducting (which closes the damper), and positive pressurisation to prevent gas ingress. This can be upgraded to have a blast resistance in the initial construction (most ratings vary of 0.3 to 0.7 bar), but bunker type designs can go further although the cost escalates.
4) Some problem areas which need to be considered are: -
   a. Will the existing building be 'fit for purpose' if the plant is expanded? This requires a risk assessment on the new hazards which are presented from the expansion.
   b. Many old Control Buildings have windows, which in a hazardous plant, is not satisfactory especially with the latest CCTV technology negating any requirement to view the plant through windows.
   c. Some control buildings were found not to be pressurised and cannot be converted easily due to the fact the building has been designed with offices, rooms, workspace for administration personnel and so on. Firstly, all non-essential personnel should be re-located away from the Control Room and then a study undertaken to improve the control centre integrity.
   d. In most older designs it is almost impossible to make the Control Building blast resistant and so solutions are needed such as constructing an annex adjacent to the control room building so that the personnel can escape into a safe haven (this has been done on offshore platforms as a Temporary Safe Refuge) – the container type facility has its own breathing air supply and provisions for survival. This is particularly useful for plants handling toxic gases (accidently released) which will usually disperse in a few hours.

It could be possible to design the annexe as a blast proof enclosure and some owners have converted the old Control Room to an unmanned enclosure with the new annexe housing a control system upgrade (DCS electronics occupying a smaller area).

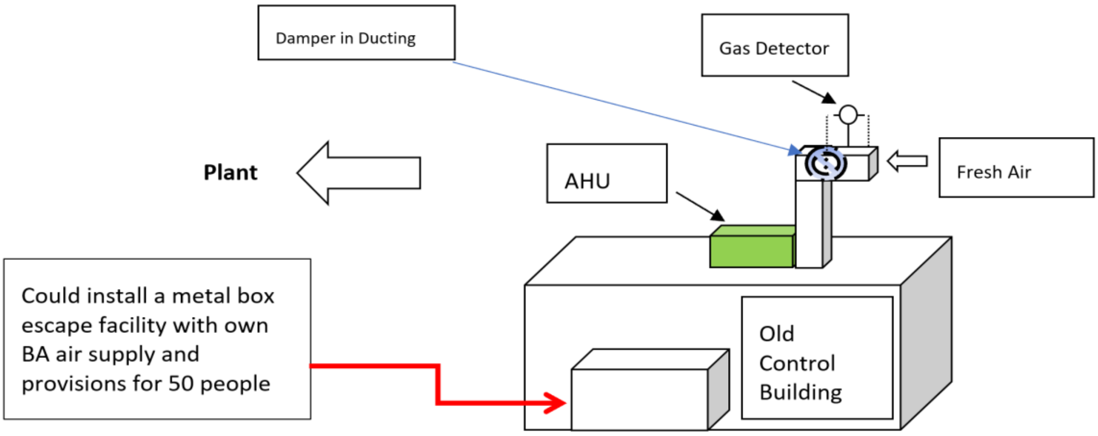


Figure 4 – Control Room Protection for Workforce

If possible, the Control Building should face 'end-on' to the process area and the air intake should face away from the process. Note: adding new plant may compromise this.

<u>Problem Areas</u>

1) The cost of converting a control building into a blast proof structure is prohibitive and relocation is the only option.
2) Overpressures from blast conditions should be profiled during any new construction or revamped plants to establish whether the Control Building is vulnerable.
3) This also applies to switchgear buildings.

<u>Lessons Learned</u>

1) Careful siting of this important structure is paramount bearing in mind future expansion phases for the plant.
2) The building must not be too small – and it should be ergonomically attractive for the Operation's workforce.

3) Many mature plants have multi-purpose buildings which are permanent offices for non-Operations Personnel. This should be avoided due the increased exposure to personnel who do not really need to be on-site.

Constructing New Units on Congested Sites

The introduction of new units into an existing site will require a detailed risk assessment to assess the fire/explosion risk potential. Where the site is already compact the following impacts should be studied.

1) The cross-exposure of fire spread should be assessed. Usually, roadways will give some firebreak protection, and these should not be built over.
2) The main risk will often be from a VCE, and this should be estimated; a risk study on the inventories can easily identify the necessary spacing between old and new units.
3) Where terracing is included, and the new plant footprint is at a different elevation to the existing site – the risk of flammable product transfer or water flooding needs to be checked. A drainage flow diagram will identify where released product, firewater and rainfall will accumulate and where new open drainage gulleys are needed.
4) If the new unit handles toxic chemicals, then the location needs careful consideration, and it is advisable to try to position the unit at a sufficient distance away. This may increase piping and cabling requirements but is necessary to avoid making changes to the existing plant to safeguard the workforce during their visits.
5) The risk to the existing Control Room has been discussed above and requires to be investigated.
6) The utilities exposure should also be assessed if new units are to be built adjacent to a non-hazardous area.
7) Perhaps the most important factors are:
   a. The impact of piling near to existing facilities.
   b. The new firewater supply route – is this compromised? There may be a higher firewater demand particularly when there is a change of fire zone envelope area. Firewater is normally delivered from two different directions (to ensure one route is always available).
   c. Drainage hydraulics for rainwater, firewater run-off as well as hydrocarbon. Note: revised rainfall rates are now being incorporated in plant drainage due to the effects of climatic change.
   d. Emergency Response – access to the older plant for firefighting vehicles, evacuation – from all directions is paramount and therefore a major factor in the layout design.

Revamping Live Plants

This is a very common activity which is intended to increase the production capacity, product quality, range and increase the efficiency to improve the rate of return. It also presents one of the most difficult challenges as often the owners wish to continue operations whilst some of the changes are to be implemented. Revamping usually translates as modernisation.

The following comments are offered with respect to safe implementation: -

Design Phase

1) Feedstock Compatibility – any attempt to revamp a plant should include a review of the suitability of the Material of Construction of the existing sections with respect to change of feedstock (corrosion, temperature or pressure change).
2) The design margins available in the existing plant which is to be de-bottlenecked. This will identify whether or not new equipment is required and internal changes such as re-traying columns, upgrading pump impellors, compressor rotors and so on.
3) Careful investigation on whether increased operating pressures/temperatures/flows can be tolerated in the plant. Any de-rated equipment/pipework needs to be identified and compared to the new process conditions. Thus, accurate up-to-date inspection thickness data must be available.
4) The key question is 'Will any existing system be subject to Operation outside its Design Operating Envelope?'. Pay particular attention to new relief loads and checking PSV/header sizes, increased or low temperatures (brittle fracture). Changing the relief load and composition may cause condensation in the flare headers. Note: addition of full flow relief valves on tower overheads can cause liquid production.
5) Higher product qualities usually mean more severe process conditions, and these must be assessed. For example, more severe hydrotreating to lower sulphur content results in higher hydrogen partial pressures and temperatures (steel upgrades and more weld checks may be necessary).
6) High-capacity tower trays may result in operational limitations. Sometimes replacement column sections can be added to increase the number of trays and thereby reduce reflux rates without sacrificing separation.
7) One of the most common causes of fires is pump seal failure so adding automated shutdown valves will reduce the risk of fire escalation (make sure the emergency push button is at least 15m away).
8) Beware of increasing temperatures across air coolers as they can fail dramatically due to buckling.
9) Site excavation may involve working in areas where a previous plant or pipelines have been built. There have been many cases where unidentified 'live lines' have not been discovered and accidents have occurred.
10) Control systems may be upgraded, and a reputable contractor is imperative – probably to be based in-house during the revamp.

Construction Phase

11) The planned maintenance turnaround interval should be used to install new equipment, tie-in points, and other activities as the plant will be out of service and the risks of an incident should be lower. This will be possible in chemical facilities or some other production classes where an annual or two-yearly shutdown is used for cleaning/preventative maintenance,

but some other types of process may only have TAs every 5-7 years due to significant improvements is catalyst life or cleaning techniques.

12) Hot tapping should not be deployed if possible. Many operators prohibit this activity on safety grounds, however, certain processes which may suffer ageing effects (cooldown and heat-up may damage refractory linings) would be kept running and hot taps have to be made. The Hazop process is essential in these cases to assess whether there are any risks from shutting down and re-start.
13) Use of barriers can be made to divert toxic gases as per Case Study No.3. However, this will only be permitted in areas which are open – any confined space area should not have this type of solution.
14) The erection of towers, drums or major equipment of significant size and weight should not be carried out by manoeuvring over 'live plant' for obvious reasons. One expansion project was cancelled after a new reactor was dropped onto an existing plant.
15) The existing foundations may be able to accommodate the increased weight of larger vessels, but a structural analysis must be carried out.
16) Additional exchanger shells can normally be accommodated by building a steel support structure around the existing shells with runway beams for bundle extraction.
17) The deployment of unrated equipment in classified areas such as welding machinery, temporary power supplies, cleaning equipment and so on should be prohibited in live areas.
18) The preparation of spools (and cutting, welding, grinding and so on) should be carried out in contractor areas sufficiently spaced from the rated zones to avoid ignition sources.
19) Adequate stress analysis for piping that is being modified or where new equipment is being tied-in must be performed (particularly with tight layouts). Numbering of lines will help in the identification of the service and reduce the risk of working on the wrong pipework. Losses have occurred by cutting into blocked or undrained lines.
20) Debris which has been produced from waste materials, grinding/cutting activities and general dust is to be controlled such that it does not remain on the plant after the revamp nor find its way into the drainage networks.
21) Opening up of flanges in a 'live facility' must always be under permit (to ensure isolation is correctly enforced) and the re-installation of full bolting afterwards must be checked afterwards. There have been several major incidents caused by cutting into live lines (which were blocked or not drained). Short bolting or incomplete flanges are a serious concern.
22) Welding quality is important to prevent failures, leaks – particularly when handling gases such as Hydrogen (low molecular weight and invisible even when it ignites).
23) SIMOPs (Simultaneous Operation) studies should be carried out. This also applies to any part of the plant which is under an ORA (Operational Risk Assessment).

Inter-spacing of Items of Equipment

Expansion of existing units may encompass adding new vessels, drums, compressors, or pumps into the original unit footprint. This requires careful examination of the risks which will be introduced such as closer inter-spacing between items, running of pipework/cabling through the unit, connections to the flare and drainage systems. One of the problems noted on this type of change is location of large hydrocarbon inventories (in drums or columns) closer to fired heaters, rotating machinery. There are spacing codes such as API and NFPA which indicate minimum distances for the design which should be followed. The addition of a new furnace, cooling tower, other utility is normally straight forward (by adding this to the end of the line), however, there will cases where the expansion is substantial and should not be squeezed into an existing plot area. A new additional plot should be sought and connected into the existing site. This has an impact on the risk assessment as a separate plot can be completely fenced off for safety and security. The construction work is thus isolated and can be under a different work permit system as the welding is not 'on live facilities. Erection of the equipment should then not have any potential for 'dropped object' incidents and all unclassified machinery can be safely operated at all times. The cost of expanding the plant into a new 'green-field' area obviously increases the cost of civils, site levelling, increased piping and cabling runs but reduces the congestion and may assist the maintenance function.

Plants which are designed to be very compact can create the following problems: -

1) Exchanger bundles have to be pulled out across roadways which then restricts the firefighting accessways.
2) Elevated equipment (on multi-level structures) is difficult to service requiring craneage to be brought inside the unit often under pipe racks which cross roadways.
3) The fire risk may be increased due to close spacing and ease of spread to adjacent equipment.
4) Careful positioning of new cable runs and piping to avoid these being directly vertically above equipment is important. Passive fireproofing and/or deluge requirements need to be reviewed.
5) The congestion effect on an explosion will exacerbate the blast pressure by confining the released energy resulting in higher damage levels and the possibility of 'domino losses'.

Storage Tank Layout

The API/NFPA guidelines provide advice on the inter-spacing between atmospheric storage tanks and sphere clusters. The arrangement of optimisation of the piping tank farms is usually based on the optimisation of the piping runs and so these storage facilities can be in a single bund. Bunding has the advantage of retention of liquid leaks (and rainwater) which can then be removed under controlled discharge.

There are some important factors:

1) Storage should be remote from processing or utility areas. No pressurised bulk storage tanks should be within process areas.

2) Mixing of atmospheric tanks and pressurised storage in a single bund is not good design – the former are weaker structures, and the latter present a 'high-energy' inventory risk.
3) Addition of new tanks/spheres must not compromise the bund retention capability. For atmospheric tanks multi-tank bunds should be designed to hold at least 110% of the largest tank volume contained in the bund (assuming the tank is full plus an allowance for firewater/rainwater). Spheres only require minimal bunding and proper drainage to a safe area such as an impounding pit.
4) Mixing of vessels in one bund or enclosure with different chemicals should be assessed to prevent one area containing reactive chemicals.
5) Insertion of a storage vessel in a bund which cannot be reached with firewater deluge (from a hydrant, truck or fixed monitor) must be investigated (e.g., adding a central tank surrounded by others).
6) Isolation of inventories through external valves (manual or automatic) should be carefully considered to avoid inadvertent transfer outside the bund.
7) Sealing of piping penetrations through bund walls will prevent escalation of an incident (refer Buncefield Incident [(27)]). In 40% of plants visited – poor sealing was noted.
8) Note: inter-tank spacing of less than one diameter is common in many tank farms, where possible spacing of four diameters will almost certainly result in only a single tank loss under any fire case event.
9) With exceptionally large tanks over 100,000 m^3 – should be located in their own bund. Firefighting is extremely difficult, and it may be best to let the fire burn out.

Reducing the Potential for Ignition Sources

The main concern with all plants which handle flammable/explosive materials is Loss of Containment (LOC). However, in certain types of facilities there are very few sources of ignition. These are the result of: -

1) Locating tank and sphere plots away from roadways (in particular away from highways).
2) Preventing unnecessary traffic within the offsites boundaries (encouraging walking and bicycle use).
3) Selecting intrinsically safe electrical and instrumentation which does not provide ignition potential.

Flare/Vent Locations

The location of the flare(s) on a plant is important as they provide a continuous ignition source.

1) Flares should be remote from process areas or any other potential source of flammable release.
2) Similarly, Vents must not discharge over process areas (in fact these should be eliminated in the design phase within any on-site plant).
3) It is preferable to discharge all PSVs to flare systems (to avoid a vapour cloud being produced).

Plant Drainage

This is one of the most important aspects of the design: -

1) All drainage channels, trenches or piping must be designed to free flow to a safe location. Thus, sloping is critical without restriction and there are hydraulic equations for this.
2) Access for cleaning of open drainage should be provided which is usually from a parallel roadway.
3) The water table must be taken into account for drainage as buoyancy effects can lift drainage ducts (during rainy seasons). Note: Expanding a site by paving may alter the soakaway rate and form pools.
4) All Hydrocarbon based drainage should flow through a closed system to a pressure vessel which can be pumped out.
5) Impounding pits for hydrocarbon drainage must have the capability for rainwater to be pumped out.
6) Deep drainage channels and sewers represent a Confined Safety Exposure.
7) Gas accumulation must be avoided in drainage systems.
8) Run-off calculations need to be prepared for expanded plants to ensure free flow away and revised collection rates. Onshore/Offshore flow checks after expansion of a plant can be performed by using firewater.
9) Plants which retain rainwater or where the flooring is always wet will promote increased corrosion of supports and damage to passive fireproofing.

Concluding Remarks

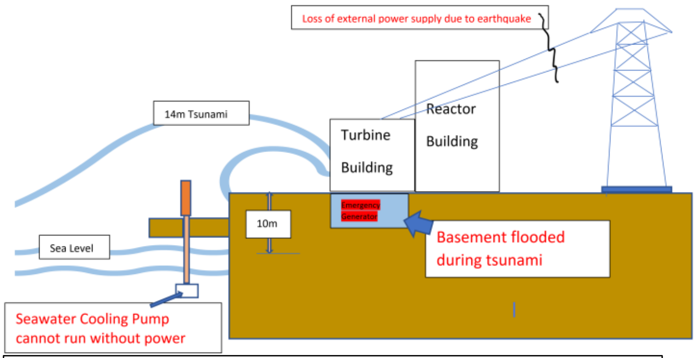
The objective of this paper is to highlight that any site hazard assessment must include an extensive review of the entire facilities not only including the new units and equipment but also any impact on the finer details of the existing site. This is illustrated in Case Study No.1 where the power supply for the entire production complex (and all production) could have been lost through an explosion from a downstream unit. Economically attractive design projects which minimize piping and hence inspection and maintenance costs can lead to a higher risk of loss if they are not identified as exposures and solutions are implemented.

Case No.2 showed the risk of locating Horton Spheres carrying an inherent BLEVE risk close to major process unit inventories could create an environment where a loss of containment could escalate into a 'domino effect' and destroy the entire complex.

Risks during construction (Case Study No.3) must also be addressed such as protecting the project workforce against a possible toxic release is paramount to safety.

Perhaps the most important location on any facility will be the Control Room and its continuous availability not only to operate/shutdown the plant under all conditions but also to offer any personnel on-site a safe haven (Case Study No.4).

Losses have occurred throughout history which perhaps could have been prevented by a more thorough risk assessment and examples below have been selected to supplement the above Case Studies:



The accident [21] was triggered by the Tōhoku earthquake and 14m tsunami on Friday, 11 March 2011 which swept over the plant's seawall and then flooded the lower parts of reactors 1–4. The earthquake cut off the external power supply to the coolant circulating pumps and the basement flooding caused the failure of the emergency generators.

Figure 5 – Loss of Power at Nuclear Plant

<u>Fukushima Nuclear plant</u> – loss of key utilities (previously highlighted in Case Study No.1) during the tsunami hampered shutdown. On detecting the earthquake, the active reactors automatically shut down their normal power-generating fission reactions. The electrical grid failed, and the emergency diesel generators automatically started. Critically, these were required to provide power to the pumps that circulated coolant through the reactors' cores to remove residual decay heat. The resultant loss of reactor core cooling led to three nuclear meltdowns, three hydrogen explosions, and the release of radioactive contamination in Units 1, 2 and 3 between 12 and 15 March. The spent fuel pool of previously shut down Reactor 4 increased in temperature on 15 March due to decay heat from newly added spent fuel rods but did not boil down sufficiently to expose the fuel.

<u>Comment</u>: All Critical utilities must be operational at all times particularly when these are required to shut down the plant and they should also be better protected from natural perils by building on elevated ground or duplication (back-up) at an in-land location.

The disaster [22] occurred in a refinery, 10 kilometres (6 miles) south of Lyon, France, on 4 January 1966

Toppled sphere from BLEVE explosion force

Figure 6 – Damaged site at Feyzin

<u>Feyzin Refinery</u> – A BLEVE event occurred through poor design (previously highlighted in Case Study No.2). The pool of propane in the bund caused the storage tank to be engulfed in flames, which produced a Boiling Liquid Expanding Vapour Explosion (BLEVE) when the tank ruptured. This resulted in a fireball which killed and injured firemen and spectators. Flying missiles broke the legs of an adjacent sphere which also then suffered a BLEVE. Three further spheres toppled due to the collapse of support legs which were not adequately fire protected. These vessels ruptured but did not explode. A number of petrol and crude oil tanks also caught fire. The conflagration took 48 hours to bring under control. This incident resulted in the deaths of 18 people, the injury of 81 and extensive damage to the site.

<u>Comment</u>: The BLEVE exposure should have been eliminated at the design stage - refer the notes under Case Study No.2.

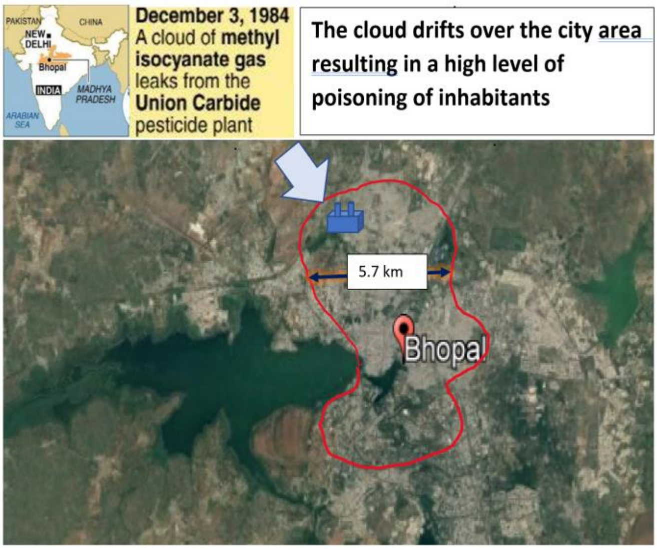


Figure 7 – Methyl Isocyanate Cloud Drift over Bhopal Districts

<u>Bhopal</u> – Toxic Release[24] – inadequate protection of workforce and surrounding areas (previously highlighted in Case Study No.3). The Bhopal disaster was a gas leak incident at the Union Carbide India Limited (UCIL) pesticide plant in Bhopal, Madhya Pradesh, India. Over 500,000 people were exposed to methyl isocyanate (MIC) gas. The highly toxic substance made its way into and around the small towns located near the plant. The cause of the disaster remains under debate. Some argue that poor management and deferred maintenance created a situation where routine pipe maintenance caused a backflow of water into a MIC tank, triggering the disaster; others argue that water entered the tank through an act of sabotage.

<u>Comment</u>: The siting of a toxic chemical plant in a highly populated District was a very poor concept. The maintenance and inspection functions were almost non-existent judging by the number of inoperable safety systems and plant operation/ maintenance procedures were not followed.

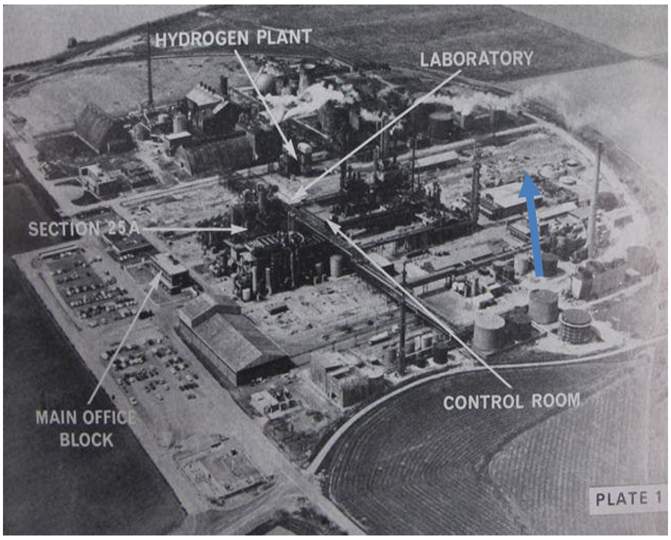


Figure 8 – Explosion at Flixborough (poor Control Room Siting)

<u>Nypro UK Explosion 1st June 1974</u> – the site at Flixborough was severely damaged by a large explosion[25]. Twenty-eight workers were killed and a further 36 suffered injuries.

It is recognised that the number of casualties would have been more if the incident had occurred on a weekday, as the main office block was not occupied. Offsite consequences resulted in fifty-three reported injuries. Property in the surrounding area was damaged to a varying degree. Eighteen fatalities occurred in the control room as a result of the windows shattering and the collapse of the roof. No one escaped from the control room. The fires burned for several days and after ten days those that still raged were hampering the rescue work.

<u>Flixborough (Nypro UK) Explosion</u> - Prior to the explosion, on 27 March 1974, it was discovered that a vertical crack in reactor No.5 was leaking cyclohexane. The plant was subsequently shutdown for an investigation which identified a serious problem with the reactor and the decision was taken to remove it and install a bypass assembly to connect reactors No.4 and No.6 so that the plant could continue production. A 20-inch bypass system ruptured, which may have been caused by a fire on a nearby 8-inch pipe. This resulted in the escape of a large quantity of cyclohexane subsequently found a source of ignition. There was a massive vapour cloud explosion which caused extensive damage and started numerous fires on the site. A plant modification occurred without a full assessment of the potential consequences. Only limited calculations were undertaken on the integrity of the bypass line. No calculations were undertaken for the dog-legged shaped line or for the bellows. No drawing of the proposed modification was produced.

<u>Comment</u>: This accident changed the design and location of Control Rooms worldwide and mandated the enforcement of Plant Modification/Change Procedures, HAZOPs, Design Codes for Pipework: pressure testing of flexible pipes/bellows on all installed modification works. Maintenance Procedures were tightened for recommissioning, SIMOPs was introduced. The incident happened during start up when critical decisions were made under operational stress. In recent years behavioural training in handling upset conditions and also risk avoidance were introduced.

Figure 9 – Remainder of Piper Alpha

An explosion and resulting oil and gas fires destroyed Piper Alpha on 6 July 1988, killing 167 men, including two crewmen of a rescue vessel; 61 workers escaped and survived. Thirty bodies were never recovered. The total insured loss was about £1.7 billion, making it one of the costliest man-made catastrophes ever. At the time of the disaster, the platform accounted for approximately ten percent of North Sea oil and gas production. The accident is the worst offshore oil disaster in terms of lives lost and industry impact[26].

Piper Alpha was an oil platform located in the North Sea approximately 120 miles (190 km) north-east of Aberdeen, Scotland. It was operated by Occidental Petroleum (Caledonia) Limited and began production in 1976 initially as an oil-only platform but later converted to add gas production.

During the late 1970s, major works were carried out to enable the platform compress gas for export requirements (Gas Conservation Module added). In the late 1980s, major construction, maintenance, and upgrade works were planned by Occidental and by July 1988 six major projects were in progress. Therefore, Piper continued to export oil and to export Tartan gas. The accident is thought to have occurred in the condensate pumping area where a leak was ignited and caused a major explosion. Various scenarios were investigated (flange leak); vibrating pipework which failed.

Comment: The main questions are:

Whether the modifications (including new modules) underwent a thorough risk assessment before their implementation?

Was the platform extended beyond its physical capabilities?

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