HAZARD ASSESSMENT OF LAYOUT

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As part of a new work on Plant Layout, an I.Chem.E. Working Party has developed a hazard assessment scheme to assist in the development of layouts. This paper describes the philosophy of the approach adopted and outlines the important steps in the method.

THE ROLE OF HAZARD ASSESSMENT IN LAYOUT CONCEPTION AND DEVELOPMENT

Plant layout is the spatial arrangement of items of process equipment and their connection by pipes, ducts, conveyors or vehicular transportation. The layout engineer has to satisfy several requirements in his design. For many years various 'conventional' considerations of layout have been used. They include process, economics, operation, maintenance, construction, commissioning, future expansion, escape and firefighting, operator safety, and appearance, (Mecklenburgh (1), Kern (2)). Recently it has been realised that the environmental impact of the proposed plant has to be determined and in particular a hazard assessment carried out, (Health and Safety Commission (3)).

Hazard assessment procedures for flowsheets have been generally available, (C.I.A. (4)), but not until now, for layout. This paper outlines the procedure developed by an I.Chem.E. Working Party in producing an updated guide to Plant Layout, (Mecklenburgh (5)). Other current work includes books by Wells (6), Lees (7), Lihou (8) and papers by Comer et al (9) and Green (10).

Traditionally conventional layout design has been carried out by non graduate designers supervised by engineers, since the abilities needed are the use of codes etc. and the application of experience and common sense. However hazard assessment requires a detailed knowledge of the physics and chemistry of the process materials and therefore has to be performed by graduate process engineers in collaboration with the layout engineer and with scientists and other engineering disciplines.

A chemical plant site is split up into plots by its principal road system. The hazard assessment is accordingly in three divisions, on the plot, outside

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The first depends on the process conditions and the qualities of engineering, operation and maintenance. For fires and explosions the probability of transmission includes that of ignition and for toxic and flammable clouds that of the wind having a certain direction and speed. The damage probability is a function of the intensity at the target (overpressure, thermal radiation flux, or concentration), the duration of the incident and the strength of the target.

The total risk to a target is the combination of the risks from each source of loss of containment. A series of risk contours can be developed (reference (9)) which can lead to a number of actions. If there is room the target can be shifted. Alternatively it may be given better protection. The most economical remedy though is usually to reduce the areas of high risk by such measures as lower inventories, less severe process conditions and better engineering.

One major snag to the ideal approach is the dearth of reliability data on process equipment even though this is being slowly remedied, (UKAEA (12)). A lesser snag is the approach requires a computer (reference (9)).

Current Approach

The approach suggested in reference (5) offsets the lack of reliability data and permits manual or simple machine computation. It is in two parts which use respectively - intensity criteria and risk criteria.

The first part selects all likely sources of loss of containment and then uses critical intensities or criteria. If the intensity at the target is less than the criterion then the target is considered acceptably safe irrespective of the risk of loss of containment. The criterion reflects the degree of protection given to the target. Otherwise the target intensity can be reduced by better process design such as lower inventories or less severe process conditions or by shifting the target or source. Thus it is possible to resolve many layout situations. Probability is merely considered subjectively in choosing or rejecting the sources for investigation.

The second part is used when layout problems cannot be resolved in the first part. The approach is to take the acceptable risk at the target and ask, probably subjectively, if the risk of loss of containment is consistent with this or can be made so by improving engineering, operation and maintenance and by training operators in the correct disaster reactions. The probability of transmission is assumed to be 100% even though for fires and explosions, not all releases are ignited and for toxic releases, the wind direction varies. It is also assumed for simplicity that immediately a criterion is violated, casualties change from 0 to 100%. These assumptions lead to the proposition that if the critical intensity is violated then the risk at the target is the same as the risk of loss of containment. The design procedure is to reduce this risk to acceptable levels called 'risk criteria'.

In the first part the concept of major credible accidents can be used on the reasoning that if it is safe for the big events, it is safe for the small ones. However in the second part, the contributions from all credible sources violating the criteria have to be added, thus making for extra calculation effort.

Other Difficulties

At the moment the models for atmospheric dispersion are still being developed as our understanding of the behaviour of vapour clouds increases. It does appear though that the solution of the model equations will require computers (reference (9)). Another lack of knowledge is about the body's reaction to toxic materials, in particular in the short term which is more appropriate to layout and emergencies than the long term effects which apply to working conditions.

Even with good models, there will be uncertainties such as weather conditions and the precise point and direction of the loss of containment. This means that the models need not be too accurate but some statistical analysis is required to find the right degree of accuracy. However in the allied subject of accident investigation where the weather and leakage uncertainties are greatly reduced, more precise models are justified and probably needed. In particular the generation, trajectory and impact of missiles will have to be considered if aerial fragmentation occurred during the incident (reference (13)). However since the chance that an item is hit by a missile is so small, the consideration of missiles in hazard assessment is not likely to be justifiable.

As the subject of hazard assessment is a rapidly expanding subject, the I.Chem.E. Working Party has chosen not to include comprehensive equations etc. in its book, as they would become quickly out of date. Instead it gives ones intended for internal assessments so that the engineer is given indications of how to improve the layout, but not to justify it.

Justification of layouts to the regulatory authorities should be undertaken by or in conjunction with, experts familiar with the current knowledge of hazard assessment.

CRITERIA

Hazard Intensities

This may be summarised as:

a) Flammability. Lower flammable limit (LFL), (e.g. CRC (14)).

b) Toxicity. Immediately dangerous to life and health (IDLH) concentrations, (Mackinson (15)).

c) Explosion. Incident overpressure from surface burst, (Kletz (16)).

d) Thermal Radiation. Incident flux

All these intensities decrease with distance and the critical values depend on the type of target and protection provided, e.g. whether plant items, roads, buildings, vegetation, employees, the public etc.

Risk Criteria

The acceptable risk from a plant is based on the risk to a healthy individual from normal life and on the number of people likely to be killed.

Plant risks to the public are considered unacceptable if above the risk in normal life and ideally should be a lot less. The risk to employees can

be higher than for the public as it is assumed they are trained to react to an emergency.

Where several people are at risk from a plant, the plant risk should be correspondingly reduced. However society will not tolerate large casualties in one incident, so no risk, however small, is wanted near large concentrations of people.

ASSESSMENT PROCEDURE

The approach to hazard assessment will vary between stage 1 and stage 2 layout. In preliminary plot layout, adjacent plots are not known and so a system of hazard contours should 'surround' the proposed plot layout. This will aid the preliminary spacing of plots on the site layout. Similarly before site purchase, the surrounding community is not known and so the proposed site layout should be 'encircled' by hazard contours to aid site selection. After site purchase the stage two site layout can take account of the consequences of hazard release on a particular community item such as a school. Likewise, the effect on a particular vulnerable item like an office, from a release on a specified plot can be calculated.

The steps in the procedure are outlined below and the calculation models summarised in the annex. Further details including the full calculation methods are given in reference (5).

Stage 1 Plot Layout

a) Data. At this stage the information available includes the process design (flowsheets and equipment data sheets) on which a preliminary hazard and operability study should have been undertaken. In addition there will be a preliminary plot layout in which the more obvious considerations such as economics, operation etc. have been incorporated.

All relevant hazard data such as physical and chemical properties, flammable limits, combustion properties, toxic limits, physiological effects etc. should be collected, collated and recorded.

b) Minor Leaks and Area Classification. All sources of small but likely losses in (reasonably) normal operation should be identified. For toxic materials this study will determine ventilation requirements. For flammable fluids it will define the electrical hazard area classification zones, (BS 5345 (17)) and the hazard areas for non electrical ignition sources such as furnaces.

c) Major Sources of Leak. The plant should be divided into sections that can be isolated from each other either by valving which can be rapidly closed in an emergency or by reason of being a separate process operation. By this means the inventories of the major sections of the plant and hence the maximum amount of material which could escape may be determined.

Those sections which are likely to lead to loss of containment by vessel or pipeline failure etc. are ascertained by a review of the operating conditions and procedures.

d) Catastrophic Failure of a Pressure or Gas Source. This can occur when a fluid is kept above the atmospheric boiling point under pressure and is suddenly released to form an instantaneous vapour cloud.

The size of the cloud should be calculated and thence the following sets of circles determined.

i) Distance the cloud drifts to LFL.

ii) Overpressures contours.

iii) Radius of fireball.

iv) Flux from fireball which puts people at risk.

v) Isopleths of toxicity in the open and the likely penetration into buildings.

If there is a liquid residue after the failure, it should be treated as in step (f).

e) Major Steady Leakage from a Pressure or Gas Source. Like step (d) this can occur for a fluid kept above the boiling point but, by issuing through a finite size hole, gives rise to a jet which decelerates into a plume.

The rate of escape should be determined and then the following calculated.

i) The distance the jet (or possibly the plume) takes to reach the LFL.

ii) Thermal flux contours for jet fire.

iii) Isopleths of toxicity in the open and the likely penetration into buildings of varying airtightness.

If there is liquid escaping which can form a pool, it should be considered as in the next section (f).

f) Failure of Liquid Source. This happens with a liquid kept below its atmospheric boiling point. If the top of the container fails, the liquid will evaporate or burn from the vessel. With other failures the liquid will run out and form a pool which will then either evaporate or burn.

From the rate of evaporation or burning can be found

i) The distance the plume travels before being diluted to the LFL.

ii) Thermal flux contours for the pool fire.

iii) Isopleths of toxicity in the open and the likely penetration into buildings of varying airtightness.

g) Internal Plot Layout. This is mainly determined, for hazards, by the electrical classification scheme discussed in step b and by the need to locate permanent ignition sources in safe areas.

Except in very large plots there is not sufficient room to mitigate the effects of overpressure on equipment or the toxic effects. However it will be possible to site vent discharges to prevent the ignition of emergency releases. It may be possible to space items to stop the spread

of fire and avoid equipment collapsing onto other equipment. The position of pools should be away from equipment and pool areas should be as small as possible.

The results of the studies in steps d, e and f should be used to position the control room and other plot buildings containing personnel (HSC (3), CIA (19)). Such buildings should be so situated and protected to resist the expected overpressures and fire radiation and allow escape. They should not be in electrical classification zones and internal air supplies may be required when there is the risk of toxic release. If location inside a classified zone is unavoidable, protection by pressurisation may be used, (BS 5345.5 (18)).

h) External Plot Separations. In order to prepare for site assessment, the effects of the various losses of containment within the plot should be combined. One useful way of doing this, at this level of assessment, is to think in terms of the maximum credible incident. Thus the incidents that give the biggest extent of contours should be noted. However, it is possible that the whole or large parts of the plot will be on fire, and the thermal radiation contours must thus be based on the flux of all the relevant plot items on fire.

It may be obvious at this stage, that the contours are too extensive, that is, the plot too hazardous. Various remedial measures described in the next section may be therefore considered before proceeding to site assessment.

Stage 1 Site Layout

a) Data. The data available includes a first site layout plus the hazard assessment of the various plots in the form of contours.

b) Vulnerable Items. These should be identified and could include the site main roads, central offices, emergency services and key commercial plants. They could themselves be hazardous to a certain extent, especially with regard to fire and therefore their thermal radiation contours should be found.

c) Internal Site Layout. The size and arrangement of the proposed site are adjusted so that the relevant criteria are not violated at the vulnerable items. In particular there should not be any escalation of incident from one plot to the next (domino effect).

d) External Site Separation. To aid site selection hazard contours should be 'drawn' around the site.

As flammability and thermal flux are fairly local in effect the contours will be based on the various plots placed near the edge of the site. Overpressure contours can probably be based on the maximum sized UCVE occurring on the site, though two sources may be considered for very large sites. Similarly the toxicity contours can probably be those of the worst case unless there are possible releases of materials with very different physiological effects.

e) Site Selection. It may be found from steps (c) and (d) that the site and its surrounding 'sterile' zone are going to be too large irrespective of the location chosen. In this case remedial actions given in the next section should be applied to the appropriate plots and then the site reassessed.

The hazard assessment of the site will indicate the kind of location needed, for example hazardous sites cannot be put in densely populated areas.

Stage 2 Site Layout

a) Data. The site layout has to be accommodated to the site purchased which means that the plots may be in a different arrangement from which the stage 1 site assessment was based. In addition the vulnerable and hazardous installations outside the site are now known.

b) External Vulnerable Installations. As well as the internal vulnerable items, items external to the site should be identified and marked on a map of the area around the site. These could include roads, railways, housing, schools, hospitals, factories and vegetation.

c) External Hazardous Installations. Ideally existing adjacent factories should provide a site hazard assessment for the use of the new site owners.

d) Internal Site Layout. This is now repeated but within the constraints of the chosen site. With the known size of site it will probably be found that not all the criteria for overpressure, flammability, toxicity and thermal flux can be obeyed. At this stage these violations should be noted but not resolved.

e) External Site Spacing. Hazard contours are produced as for stage 1 site layout but the contours can be laid on the map around the site giving the position of the vulnerable installations. Adjustments are made to the site layout so that most situations obey the various criteria. As in (d) the violations should be noted.

Stage 2 Plot Layout

a) Data. A much more detailed layout is available for stage 2 assessment compared with stage 1. This detailed layout is based on more comprehensive process and project engineering designs. Deficiencies found in the required hazard properties when stage one was undertaken, should have been largely remedied.

b) Calculations. Electrical zone classification etc. and the major leak calculations are repeated with the more complete data.

c) Internal Plot Layout. The layout should be adjusted so that the spread of fire from one item to another and the collapse of one item onto the next are limited as far as the size of the plot allows. Escape, fire fighting and other emergency procedures should be accommodated in the layout.

Emergency vents should be spaced sufficiently far from ignition sources such as furnaces.

The position and degree of protection of the control room and other plot personnel buildings must be consistent with the appropriate overpressure and thermal flux criteria. If not, the probability of a loss of containment causing casualities in the control room has to be within

acceptable limits. This will mean improving the engineering standards of the plant and emergency escape procedures from the buildings (references (3) and (19)).

d) External Plot Separations. The combination of the effects of the various losses of containment should be carried out as in stage 1. However, unlike stage 1 layout, the positions of adjacent plots are now known and it may be found that the forecast intensities, particularly flammability and thermal flux in the adjacent plots, are greater than the appropriate criteria. Rearrangement of the items within the plots may remedy this.

Final Assessment

With the comprehensive plot layout assessments, the internal and external site assessments should be repeated. Hopefully most situations can be resolved within the appropriate intensity criteria. Those that are not have to be reconciled with the relevant criteria of risk. This can be quite lengthy as several sources of loss have to be considered.

The results of the final overall assessment may well have to be submitted to the regulatory authorities, in which case expert advice should be sought in its preparation.

APPLICATION TO LAYOUT DEVELOPMENT

The preceding assessment identifies the sources of hazard and the vulnerable targets and quantifies the effects of release from the sources on the targets. It may well then be necessary to alter the process and the layout to reduce the effects on the targets to acceptable levels. The first three methods given below are concerned with reducing the intensities at the target to below the appropriate criteria. The fourth deals with containment of the hazard to reduce the risk to the acceptable level when violation of the intensity criteria cannot be avoided.

Elimination and Reduction of the Hazard

The purpose is to reduce or even eliminate the potential hazardness of a loss of containment at source. Methods include the use of less hazardous process materials or conditions and the reduction of inventories by having smaller vessels and pipes or installing isolating valves so that there is less material to escape.

Separation of Source and Target

If the hazard cannot be removed the first thought is to shift the hazard from targets. However distances cannot be extended indefinitely because of the increased chance of loss of containment in long connecting pipelines and because of the constraints of plot or site size.

Protection of Target

When it is not possible to place targets sufficiently afar from the hazard, protection of these vulnerable targets should be considered so that the consequences of the event may be minimised and the danger of escalation reduced.

a) Explosion. Methods are available for the structural design of buildings to resist an UVCE and a typical application would be for control buildings (references (3) and (19)).

b) Fire. Fire protection is applied to structures and cables so that they will outlast the fire. Conventional thermal insulation provides some fire protection and uninsulated equipment may be protected by the provision of fixed sprays as is often done in the case of storage tanks. The fire resistance of buildings can be increased by the elimination of wood and plastics and in some cases, windows.

c) Flammability. Electrical equipment and instruments that are within possible areas of flammable cloud and plumes, must be intrinsically safe or be made flameproof.

Dispersion aids such as steam curtains and water walls may be considered near furnaces etc. to prevent the ignition of flammable clouds.

d) Toxicity. Control buildings may, where necessary, be designed as places of refuge from the effects of toxic leakage.

Containment of Hazard at Source

There are various ways of reducing the chances of a hazard occurring as opposed to preventing it or reducing its size. As the hazard can still occur it is preferable not to rely completely on containment but also use the previous methods for the protection of the target and separation of target and source as well.

Containment methods include better standards of engineering, construction, operation, maintenance and modification. Also vents and drains should be sited safely, non-return valves and ventilation employed and blast walls considered.

CONCLUSION

The scheme developed by the I.Chem.E. Working Party is meant for the guidance of layout development and not for the justification of layouts. This policy was adopted because the rapid development of subject would render any comprehensive scheme needed for justification, quickly out of date. However a more simple methodology stands a better chance of remaining valid longer. To improve this chance, the calculation methods have been put in an appendix to the book (reference (5)) away from the description of the general approach to layout assessment. Engineers can therefore substitute their own algorithms where necessary without altering the general approach. In particular the equations given in the book are geared to manual computation at some sacrifice to reality. For example the dispersion model for heavier than air vapours requires machine computation (reference 9) and this could be inserted into the scheme.

The overall approach to hazard assessment of layouts outlined in this paper should remain valid until the desired improvements in reliability data are achieved.

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ANNEX

CALCULATION MODELS

1. *Instantaneous Release Under Pressure*

1.1 Weight Released

Gas:- contents

Flashing Liquid:- vapour from thermodynamic flash entrainment = vapour, subject to availability (Kletz (16))

1.2 Distance to LFL — Gaussian dispersion (TNO, (22))

1.3 Explosion Overpressure — TNT (Kletz (16))

1.4 Fireball — Stoichiometric premixed (small) (Hardee, (20)); Diffusion controlled (large) (Fay, (21))

1.5 Distance to safe toxic limit — Gaussian dispersion (TNO, (22))

1.6 Seepage into buildings — Air change by convection

2. *Steady Release under Pressure*

2.1 Leakage rate — Gas:- choked flow; Flashing Liquid:- choked flow with vapour from thermodynamic flash

2.2 Distance to LFL — Jet dispersion (Cude, (23))

2.3 Jet Flame — Momentum entrainment (Craven, (24)) with flame pointing at target

2.4 Distance to safe toxic limit — Gaussian dispersion with 30 min mean concentration (TNO, (22))

2.5 Seepage into buildings — Air change by convection

3. *Release of Liquid at Atmospheric Pressure*

3.1 Leakage Rate — Bernoulli

3.2 Pool Spreading Rate — Gravity slumping (Shaw (25))

3.3 Pool Evaporation Rate — Ground or water cooling (Cryogens, Shaw (25)); Wind action (Pasquill (26))

3.4 Distance to LFL — Gaussian dispersion with in-cloud concentration (TNO (22))

3.5 Pool or tank fire	Cylindrical Flame (Thomas (27) Stark (28), Burgess (29)) Flame pointing at target
3.6 Distance to safe toxic limit	Gaussian distribution with 30 min mean concentration (TNO (22))
3.7 Seepage into buildings	Air change by convection
4. *Receiver temperature*	
4.1 Away from flame	Stefan's equation and convection
4.2 In flame	Flame temperature
4.3 In burning liquid	Boiling point of fuel
4.4 Below liquid level in tank	Boiling point of contents
4.5 In water drench	Up to boiling point of water
4.6 Under insulation	Conductivity and thermal capacity effects

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