Incident

Flixborough: Lessons which are still relevant today

Robin Turney

Summary

After 40 years, Flixborough still ranks as the worst mainland process plant disaster in the UK. The paper will review the official report into the disaster and, drawing on current standards and more recent incidents, will consider how relevant the lessons are to the process industry today. Aspects which will be covered include:

- the control of modifications;
- understanding of vapour cloud explosions;
- occupied buildings;
- competence and organisational change;
- safety culture.

Particular emphasis will be given to issue of management competence and the organisational changes that took place on the site before the incident occurred. It will question whether the systems advocated today would be fully effective in dealing with the unplanned changes that were at the root of the disaster.

Keywords: Flixborough, modification, management of change, explosion

Introduction

Flixborough was not the first serious accident to occur in the process industries during the 60's and 70's. It did however result in a step change in the consideration of process safety and introduced changes that are still relevant forty years later.

Interest in process safety had started before 1974. The IChemE Hazards series of symposia started in 1960 and the first symposium of the European Federation of Chemical Engineers (EFCE) Loss Prevention Working Party was held in May 1974. The Loss Prevention Journal was being published by the American Institution of Chemical Engineers; within ICI HAZOP was already a well-established procedure in the design of new plant and Trevor Kletz was producing his Safety Newsletters.

Flixborough was not only the most serious incident to have occurred in the UK process industry, it was also one of a series of serious explosions and fires that occurred during the 1970's in both Europe and the USA. As noted in the reports of the Advisory Committee on Major Hazards the capacity of some hydrocarbon processing units had increased tenfold in the twenty years prior to 1975 (ACMH First & Second Reports[1]).

Following Flixborough there was a significant increase in the attention given to process safety. The Loss Prevention Bulletin (LBP) was first published in the months following Flixborough[2]. The Health and Safety at Work Act was introduced into the UK and the Advisory Committee on Major Hazards was established towards the end of 1974 to advise on '...measures to control.. such installations'. This led to the establishment of the Notification of Installations Handling Hazardous Substances Regulations, a predecessor to the Seveso Directive and the UK COMAH Regulations.

This paper is based primarily on the findings of the Court of Inquiry[3] established following the explosion and will attempt to show how the lessons learned from the event relate to current good practice in process safety.

The explosion

A massive explosion equivalent to between 15 and 45 tons of TNT occurred at 4:35pm on Saturday 01 June 1974. The consequences were severe with 28 of those working on the site being killed, together with 36 onsite and 53 offsite injuries. It resulted in almost complete destruction of the plant and extensive offsite damage to approximately 2000 buildings. A brief recap of the main elements leading up to the accident is as follows.

The plant was operated by Nypro Chemicals which at the time of the accident was owned jointly by Dutch State Mines and the National Coal Board (NCB). The plant had been commissioned in 1967 to produce caprolactam, an intermediate in the production of nylon, a revised process introduced in 1972. A key part of the revised process involved the oxidation of cyclohexane by air in a series of six large reactors at a pressure of 8.8 kg/cm² and a temperature of 155°C, above its atmospheric boiling point. These reactors were inter-connected by 700mm diameter, metal expansion bellows to accommodate thermal expansion.

Two months prior to the accident at the end of March a crack was noticed on number 5 reactor and the plant was shut down. A meeting of the site management team agreed that the reactor would be removed and, to enable production to continue, a section of pipe was inserted between the bellows to take the place of the missing reactor. The modification was fabricated onsite without any engineering drawings, calculations or hydraulic testing, the new pipe was inserted, supported by scaffolding, and the plant restarted. No account was taken of the turning moment that would be placed on the new pipe due to flow of fluid and the process pressure or the fact that the bellows would be subject to shear forces for which they were not designed. The scaffolding support was

0260-9576/14/$17.63 + 0.00

IChemE

completely inadequate to resist these forces.

The plant then ran without further problems until at the end of May when it was shut down again to repair a leak. Whilst the plant was being restarted the temporary bellows/piping failed, the temporary pipe jack-knifed and many tons of boiling cyclohexane were released. This rapidly created a vapour cloud which ignited with a force estimated to be equivalent to between 15 and 45 tons of TNT.

The inquiry examined in detail an alternative scenario involving the initial failure of an 8" (200mm) pipe. Examination of this alternative scenario, which was dismissed by the inquiry as highly improbable, has been discussed elsewhere and is beyond the scope of this paper.

Management of change

The Court of Inquiry found the direct cause to be the release and explosion of cyclohexane

> *'….. caused by the introduction into a well designed and constructed plant of a modification which destroyed its integrity.' As noted above there was little or no engineering consideration of the way in which this pipe should be designed and installed or of the fact that the bellows were being subjected to forces outside of their design range.*

Two of the Court's recommendations key recommendations were:

> *that any modifications should be designed, constructed, tested and maintained to the same standards as the original plant.*

> *that all pressure systems containing hazardous materials should be subject to inspection and test by a person recognised by the appropriate authority as competent after any significant modification has been carried out and before the system is again brought into use.*

Whilst these are important recommendations, they do not cover all the factors that need to be considered when making changes to a plant or process. The first reference to the importance of having a robust Management of Change procedure is an article in issue 1 of LPB *Are your Plant Modifications Safe?*[2] This article includes a range of case studies covering changes to piping and valves, change of process materials and incorrect materials of construction. It finishes with a recommendation that:

> *On each works there ought to be a system for checking expenditure proposals, however small, to make sure that the correct materials are specified and that there are no unforeseen effects on the relief and blow-down system, trip system, area classification, and other safety systems. Such formal systems should require that all plant design, minor modifications, changes in process conditions, changes in operating procedures, changes in material composition are subject to thorough Hazard & Operability Studies.*

The above is extremely close to the MOC procedures used today. The application of such a system at Flixborough, together with measures recommended by the Court to ensure that sound design principles were applied to changes, would almost certainly have prevented the disaster.

The importance of robust MOC procedures is now well understood in the process industry and current best practice, such as in an IChemE training module[4] would include all of the above with the addition of changes to computer programmes, temporary changes as well as organisational change (an issue touched on later in this paper).

Despite this, incidents due to poor control of changes continue to occur, recent examples being those at Texaco, Milford Haven refinery in 1994[5] and at the Conoco Phillips Humberside refinery in 2001[6].

Understanding of Unconfined Vapour Cloud Explosions

Whilst there had been unconfined explosions causing significant damage before Flixborough, such as that which resulted following the failure of a LNG storage tank in Cleveland Ohio in 1944[7], methods for estimating the potential consequences were not in common use.

As noted in the by the Court of Inquiry:

> *"Although unconfined vapour/air explosions have been known to happen in other parts of the world, there is a marked scarcity of information about the conditions under which an unconfined vapour cloud can result in an explosion or what is the mechanism leading to such an explosion. We do not know to what extent it is practicable to obtain this information but if it can be obtained it would clearly be useful.*

One of the earliest approaches to determine the consequences of an explosion relied on the TNT equivalent method first described by Brassie & Simpson in 1968[8], six years before the Flixborough Explosion. In the days shortly before Flixborough took place, a paper was presented at the first International Symposium on Loss Prevention and Safety Promotion in the Process Industries exploring a vapour cloud explosion in 1968 at a Shell refinery in Rotterdam[9]. The subject was very unclear at the time. In their paper, Brassie & Simpson described the results obtained by studying the records of damage from a number of large scale explosions in order to estimate an empirical efficiency factor that could be used to convert the energy contained in gas cloud into a TNT equivalent. Tables derived from the explosion of munitions were then used to determine the extent of damage at various distances from the point of explosion. Flixborough spurred further work on flammable gas clouds and the understanding of these events, which was still incomplete even up to time of the Buncefield explosion in 2005.

Three years after Flixborough, at Hazards VI, papers on flammable gas clouds were presented by Clancy & Burgoyne[9] as well as Marshall and Burgoyne. In Clancy's paper, a method is developed to calculate the maximum quantity of vapour within the flammable region from the quantity of flammable gas or vapour released. The differences between condensed phase explosions and vapour cloud explosions means that, whilst the TNT equivalent may be used to estimate damage in the far field, it will overestimate overpressure in the near field since the peak pressure in the high density, solid explosive is roughly a thousand times higher than in an exploding gas,

0260-9576/14/$17.63 + 0.00

although the blast duration is relatively very short.

Research into vapour cloud explosions continued in the USA, UK and France during the 1970's. These provided the first indications that overpressures resulting from unconfined gas and vapour cloud explosions were generally low unless there was a strong ignition source coupled with some form of congestion, such as that provided by piping, vessels and steelwork, to introduce turbulence into the flame front. This is the basis of the multi-energy method developed by TNO. This overcame the limitations of the TNT equivalent method and provided the basis for a number of widely used computational fluid dynamic (CFD) models. The EU supported further work in the field throughout the 1980's and 90's which resulted in the validation of the Gexcon computer CFD code FLACS.

However these methods were not initially able to describe the extent of the damage which resulted from the Buncefield explosion in 2005. More detailed work was required in order to demonstrate how a number of factors, including the composition of the gasoline, the tank overflow arrangements, the weather at the time of the release as well as the trees inserted to provide a visual screen, all interacted to accelerate the flame, and thus contributed to the severity of the event. Whilst work carried out post-Buncefield greatly improved the methods available to estimate the consequences of a vapour cloud explosion the question as to whether the cloud produced a fast deflagration or a detonation is still not resolved. Large scale releases of flammable materials continue to occur resulting in flammable vapour clouds and explosions as for example at Conoco/Phillips (1989), Texas City (2005) and Jaipur (2009), see Johnson[10].

It is clear that great caution and expertise must still be used before concluding that severe consequences cannot arise following a large flammable release.

Occupied buildings

Prior to 1974 unconfined explosions on the scale of Flixborough were not generally taken into account in the design and location of control rooms and other occupied buildings. In addition there were features in the design of the buildings at Flixborough which contributed to the high number of fatalities, features which were common in many plants designed up to that time.

The control room was located close to the plant for operational reasons. However the building offered no protection against even small overpressures and the design of the building, with brick walls and the control room located on the ground floor beneath a heavy concrete floor, exacerbated the condition leading to such a high death toll. None of the 18 people in the building escaped. The plant laboratory suffered from similar deficiencies. The fact that the accident occurred at a weekend when the office block, which was also destroyed, was unoccupied prevented a much higher toll of casualties.

In their report the Court of Inquiry referred the topic of occupied buildings to a special committee (ACDS) noting that:

> *"Many suggestions were made to us as to the consequences which should follow from taking account of such a possibility. These included: the siting of offices, laboratories and the like well removed from hazardous plants; the construction of control rooms on block-house principles….."*

Following Flixborough, the Chemical industries Association developed guidance on the location and design of occupied buildings, the first edition being published in the late 1970's. Protection against overpressure was commonly incorporated into control rooms designed post-Flixborough and many control rooms on existing facilities were rebuilt to provide similar protection. Despite this, explosions and fires caused fatalities in occupied buildings in the case of Hickson & Welch[11] and BP Texas city Refinery[12].

Development of the CIA Guidance has continued with the 3rd edition being published in 2010, an overview being provided by Coates & Patterson at Hazards XXII [13,14]. Current good practice, as defined in the guide, recommends that organisations have a policy on occupied buildings incorporating the following hierarchical approach linked to inherent safety, an example of such a policy being given below.

> *The protection of people on chemical manufacturing sites should adopt the following principles:*
>
> *Wherever possible, locate people away from chemical processing and storage unless their presence is required for safe, effective operations*
>
> *Control the risks during storage and all operational phases by efficient and effective process safety management*
>
> *Ensure that the on-site buildings are located and designed to minimise the risks to the occupants by:*
>
> - *Carrying out an appropriate risk assessment for the buildings, and*
> - *Applying the results of the risk assessment to the design and continued operation of the buildings.*

The latest guidance makes it clear that all buildings which may be occupied even for limited periods of time, such as maintenance facilities, shift laboratory facilities and small on-plant control stations, need to be considered and an Occupied Buildings Risk Assessment prepared where appropriate. Whilst protection against explosion overpressure remains an important consideration the assessment also needs to consider other hazards such as thermal radiation and toxic gas.

The explosion and fire at BP's Texas City refinery highlighted the importance of considering explosion overpressure in the location and design of temporary buildings as well as the importance of reducing the number of personnel exposed during high risk periods such as plant start-ups.

Management competence

The Court of Inquiry highlighted the deficiencies in management at Nypro Chemicals which contributed to the incident. The Works Engineer, who had been a chartered mechanical engineer, had left the site some time before the incident. The Services Engineer, who was a non-chartered electrical engineer with an ONC qualification, was given a co-ordination role managing day to day maintenance activities; however, his training did not equip him to assess even straightforward mechanical engineering issues. Although arrangements had been made to make expertise in mechanical engineering available from the NCB these were not called on

0260-9576/14/$17.63 + 0.00

when the modification was made.

During the meeting to discuss what action to take following the discovery of the cracked reactor:

No-one appears to have appreciated that the connection of No. 4 Reactor to No. 6 Reactor involved any major technical problems or was anything other than a routine plumbing job, and the possible design problems and design alternatives were not discussed. Even the fact that the inlet and outlet of the by-pass pipe were at different levels was not appreciated at the meeting;

To quote from the report:

'….none of the senior personnel of the company, who were chemical engineers, were capable of recognising the existence of what is in essence a simple engineering problem let alone solving it'.

It is also surprising that the plant was restarted without any action being taken to assess the cause of the crack in reactor 5. The crack was massive, 1.8 metre long and extending through the full 95mm thickness of the vessel wall. As noted by the Inquiry a crack of this size could have led to a disastrous failure of the vessel with a major loss of containment and consequences as severe as the eventual explosion.

The report notes that:

...no-one at the meeting, save Mr Blackman, (the engineer responsible for areas 1 & 2) was seriously concerned about the wisdom of restarting without both:

(a) ascertaining the cause of the crack to Reactor No. 5 and

(b) stripping and inspecting the other five reactors to ascertain whether any of them exhibited similar faults, albeit not yet sufficiently developed to cause actual leakage;

The inquiry was clear that good practice, exercised by a properly qualified engineer, would have called for the plant to be shut down until it had been established that the other reactors were sound and free from defects. Such a shut-down would have provided more time to consider the design of the by-pass.

The Court made two recommendations in this area.The first recommendation was that:

'... when an important post is vacant, special care should be exercised when decisions have to be taken which would normally be taken by or on the advice of the holder of the vacant post.'

It also recommended that:

... it is essential that the management structure should be so organised that the feedback from the bottom to the top should be effective to ensure not only that instructions given are effectively carried out (although that is essential) but

(a) that persons given certain responsibilities are competent to carry out those responsibilities,

(b) that top management has a clear understanding of the responsibilities of individuals and the magnitude and type of demand made upon them, and

(c) that top management has a clear knowledge and understanding of the total work load placed on each individual in relation to his capacity. Even good and competent individuals have increased potential for errors of judgement when overworked. Also, in times of crisis and extreme demand it is easy to overwork the willing horses some of whom may not know their own limitations.

These recommendations are likely to have been influenced by the findings of the collapse of a spoil tip in Aberfan in 1966, which took the lives of 116 children and 28 adults[15]. The lack of technical competence was also at the heart of this disaster:

' …. the Aberfan Disaster is a terrifying tale of bungling ineptitude by many men charged with tasks for which they were totally unfitted, of failure to heed clear warnings, and of total lack of direction from above. Not villains but decent men, led astray by foolishness or by ignorance or by both in combination, are responsible for what happened at Aberfan".

The Courts recommendations are still relevant today with the current recognition that sound management systems are at the heart of process safety. It is reflected in the OECD guidance for senior leaders in high hazard industries *Corporate Governance for Process Safety*[16] where competence is one of the five key areas with a recommendation that:

'CEO and leaders assure their organisation's competence to manage the hazards of its operations, and:

Ensure there are competent management, engineering, and operational personnel at all levels. '

As noted in section 3, the control of organisational change is as important as the control of changes to the plant or process. The management deficiencies at Aberfan were the result of a reorganisation and would be identified by the procedures for control of organisational change advocated today[17]. The changes at Flixborough were however imposed on the organisation by the resignation of the works engineer and would not necessarily trigger a MOC review. It is therefore important that the organisation has the resilience to ensure that the required technical competencies are available when required. Absence of one individual, whether due to resignation, accident or illness, is to be expected and the management organisation must be able to cover such situations. Within large organisations, the necessary expertise may be available from elsewhere in the organisation but smaller organisations may need to call on consultants.

Competence is still a topic of concern and an HSE report[18] notes that:

'a review of major accidents across hazardous industries found that a lack of competence contributed to many of those incidents including:

Southall Rail Crash; BP Texas City; Piper Alpha explosion and fire; the Esso Longford Gas plant explosion; and Buncefield.'

An important aspect of competence is an understanding of the limits of that competence and the recognition of those situations when the advice of others needs to be sought. The integrity of the other reactors should have been confirmed

0260-9576/14/$17.63 + 0.00

by an expert before restarting the plant. In addition, those involved in fabricating the temporary pipe did not recognise the need to evaluate the turning moment which was imposed on the pipework from the fluid flow and the internal pressure nor the fact that the bellows should only be subjected to axial loads.

This is covered by the HSE in its guidance to inspectors[18], which requires that

> *'The Operator has arrangements in place to ensure that individuals only perform activities that they are competent to carry out. Personnel and their line managers should know which activities personnel have been assessed as being currently competent and authorised to undertake. Personnel should be made aware of the importance of only carrying out those activities for which they have been assessed as competent and for which their assessment is current.'*

Had such arrangements for staff competence been in place at Flixborough at the time of the disaster, coupled with an effective management of change procedure, it is highly unlikely that modifications would have been made without adequate mechanical design, and the disaster would have been prevented.

A second, longer term, recommendation of the Court of Inquiry was that

> *'All engineers should therefore learn at least the elements of other branches of engineering than their own in both their academic and practical training.*

Traditionally engineering courses have required a certain amount of basic engineering, mechanics etc. as part of the first or second years. Whilst many universities retain this, there are many pressures on the curriculum as process engineering increasingly includes more computing, management and elements of life science. An associated problem is that with the increasing importance of research in university funding, academic staff are much more likely to be employed because of their research speciality rather than a practical knowledge of engineering. In addition few mechanical, electrical or civil engineering courses include any consideration of process safety. It is therefore questionable as to whether university courses can be relied on to equip a graduate with all the skills necessary for work in the process industry. This demonstrates the importance of post-graduate training, such as IChemE's *Fundamentals of Process Safety* course.

As fundamental science becomes more important, engineering institutions, such as IChemE, may need to review whether their membership requirements continue to ensure a competence in basic engineering.

Safety culture

The importance of an organisation's safety culture was first recognised following the Chernobyl nuclear reactor explosion and meltdown in 1986, so it is not surprising that it is not mentioned in the Court's report. Whilst we must always be cautious in applying current standards to actions carried out in the past it is interesting to attempt to assess the safety culture which applied at Flixborough.

The Court's report makes a number of references to the level of safety at the Flixborough site, many of which appear contradictory to today's reader.

There are a number of positive comments:

> *There can be no doubt that Nypro were very safety conscious and that Mr Brenner (Safety & Training Officer) was an able and enthusiastic safety and training manager. He had created a proper system for dealing with normal hazards*

> *At no point in the inquiry was there any evidence that the chemical industry or Nypro in particular, was not conscious of its responsibilities relative to safety. On the contrary, there were indications that conscious and positive steps were continually taken with this objective in mind.*

> *We repeat that there was no evidence whatsoever that Nypro placed production before safety.*

> *We entirely absolve all persons from any suggestion that their desire to resume production caused them knowingly to embark on a hazardous course in disregard of the safety of those operating the Works.*

The above comments do not align with other comments in the report and at no point is there any mention of systems to manage process safety. There were serious omissions during the management meeting which decided to install the by-pass and despite the above comments it is clear that at certain critical times process safety was either not considered at all or given a lower priority than production.

> *the emphasis at the meeting was directed to getting the oxidation process on stream again with the minimum possible delay.*

> *no-one at the meeting, save Mr Blackman, was seriously concerned about the wisdom of restarting without ... inspecting the remaining reactors.*

> *We have no doubt, however, that it was this desire (to resume production) which led them to overlook... that it was potentially hazardous to resume production without examining the remaining reactors....*

> *We have equally no doubt that the failure to appreciate that the connection of Reactor No. 4 to Reactor No. 6 involved engineering problems was largely due to the same desire.*

We cannot rewrite history and neither Nypro nor its management were accused of breaking any of the laws or regulations in place at the time, prior to the implementation of the Health & Safety at Work Act with its wider management responsibilities. However recent inquiries, such that into Texas City or the Haddon-Cave Inquiry[19] into the explosion of an RAF Nimrod aircraft in 2006,have been much more critical of management deficiencies.

A commonly used model for assessing the safety culture of an organisation is the five step Safety Culture Maturity Model[20], developed for the HSE.

Level 1 Emerging
Level 2 Managing
Level 3 Involving
Level 4 Cooperating
Level 5 Continually Improving

0260-9576/14/$17.63 + 0.00

Currently operators responsible for high hazard operations would be expected to be at or aspire to levels 4 or 5. However looking at the information available in the Inquiry report, Nypro, and possibly many other organisations in the 1970's, would appear as level 1 or level 2. From the information in the report the management at Nypro do not seem to have appreciated or understood the full extent of hazards of the process they were operating. There are no references to the characteristics one would expect to see today in a high reliability organisation, such as the lack of complacency, the feeling of paranoia that the next accident is just around the corner, the striving to be better and the drive to find better ways of improving hazard control mechanisms.

Conclusions

Flixborough, and the other serious incidents that occurred during the 1970's, contributed to significant changes in the understanding, management and regulation of major hazard processes.

Regulations for the control of major hazard processes, introduced through the Seveso Directive and COMAH, are now well established with a further revision due to be implemented in 2015.

Management of Change procedures are now common across the process industry and cover a wider range of changes such as organisational change, although this has not eliminated incidents.

Comprehensive guidance on the location and design of occupied buildings covering both permanent and temporary buildings is now available.

Work carried out in recent years has improved the understanding of unconfined vapour cloud explosions. However large flammable releases continue to occur and the complexity of the problem will continue to require great expertise.

Guidance for board members and senior management includes the importance of ensuring that appropriately qualified, competent staff are employed. Authorities, such as the HSE have developed detailed guidance. However the disperse nature of much of the industry and ongoing re-organisations means that this is an area which will continue to require close attention.

The importance of an organisation's safety culture is now appreciated and there are indications that the safety culture of organisations today is generally much better than it was at the time of Flixborough. However much still needs to be done, particularly to ensure that the board's perception of the organisations safety culture matches that at the operational level.

Acknowledgements

The author would like to thank Martin Pitt and Robert Skelton for their helpful comments in preparing this paper, and Hans Pasman for his contributions to the section on vapour cloud explosions.

References

1. *Advisory Committee on Major Hazards*, 1st & 2nd Reports, HSE
2. *Loss Prevention Bulletin*, Issue 1, 1975, IChemE
3. *The Flixborough Disaster; Report of the court of Inquiry*, icheme.org
4. Modifications, *The Management of Change*, IChemE
5. *Explosion and Fires at the Texaco Refinery*, Milford Haven 1994, icheme.org
6. *Report on the Conoco-Phillips Humber Refinery*, HSE, icheme.org
7. Explosions at Cleveland Ohio, LPB, issue 52, 1983, IChemE
8. Brassie & Simpson, 1968, Loss Prevention Vol. 2, p91-103, AIChE
9. Clancy & Burgoyne, *Dangerous clouds*, Hazards VI, 1977, p111
10. Johnson, *Vapour cloud explosion at the IOC terminal at Jaipur*, LPB, issue 229, IChemE
11. The Fire at Hickson & Welch, HSE, icheme.org
12. Broadribb, *Lessons from Texas City*, LPB, issue 192, 2006
13. Coates & Patterson, The revised 3rd edition of the Chemical Industries Association *Guidance for the location and design of occupied buildings on chemical manufacturing sites*, Hazards XXII, icheme.org
14. Chemical Industries Association, *Guidance for the location and design of occupied buildings on chemical manufacturing sites*, CIA
15. Aberfan Inquiry, gov.uk
16. *Corporate Governance for Process Safety, Guidance for senior leaders in high hazard industries*, OECD.
17. HSE, *Current good practice HSE Human Factor Briefing Note 11*, Organisational Change
18. HSE, hse.gov.uk/comah/guidance/inspection-competence-systems
19. Haddon-Cave, *The Nimrod Review*, HMSO
20. HSE, *Safety culture maturity model*, Offshore Technology Report, 2000/49. hse.gov.uk