Process Hazard Review: The Efficient Risk Assessment of Existing Plants

Graeme R Ellis, Senior Safety Consultant, ABB Eutech Process Solutions
Daresbury Park, Daresbury, Warrington, Cheshire WA4 4BT, United Kingdom
Tel: +44 1925 741297; Fax: +44 1925 741307; Email: graeme.ellis@gb.abb.com

Introduction

Accidents continue to occur almost daily in the Process Industry resulting in fatalities and injuries, serious harm to the environment and major damage to plant equipment. The ammonium nitrate explosion at Toulouse in 2001 resulted in 30 fatalities and has led to calls in France to re-consider allowing process plants to operate near to population centres. Whilst significant quantities of flammable, toxic and eco-toxic substances are processed, all those working in the industry need to make every effort to ensure that suitable and sufficient protective measures are in place.

As a result of several high profile accidents in recent decades the industry now operates under strict legislative controls such as the ‘Seveso II’ Directive in Europe and the OSHA Process Safety Management standard in the USA. Companies are required to carry out risk assessments on all their hazardous operations to demonstrate that ‘all measures necessary’ have been taken to prevent and mitigate the effects of an accident.

This paper describes the Process Hazard Review (PHR) methodology that was originally developed in the early 1990’s for the periodic assessment and assurance of operating plants. More recently PHR has been used extensively in the United Kingdom to meet the predictive requirements of safety reports under the Control of Major Accident Hazard (COMAH) Regulations. PHR is a well-structured methodology that has proven to be effective in quickly identifying and assessing major accident hazard scenarios. The approach has been well received by the UK regulatory authorities.

Safety Assurance

Nowadays almost all hazardous process plants have been subjected to safety studies during their design. This typically involves the use of a hazard identification technique such as a Hazard and Operability (HAZOP) study. HAZOP is a team approach using a set of guidewords to consider potential deviations from the design intent. It has proven to be a very effective design tool to ensure that likely deviations during normal plant running have been considered allowing appropriate controls to be put in place.

Investigations following major accidents in the Process Industry have revealed that the root causes are rarely related to the failures during normal plant running. The common themes from these accidents are errors during maintenance activities and non-routine operations or due to poorly considered plant modifications. Such causes are unlikely to be considered in depth during a standard design stage HAZOP study when many of the key operating and maintenance procedures have not been fully developed.

At Flixborough, UK in 1974 a poorly designed temporary by-pass line failed releasing 30-50 tonnes of cyclohexane leading to an explosion that killed 28 people. At Bhopal, India in 1984 a maintenance error is believed to have allowed water into a tank of methyl isocyanate causing a release of toxic gas killing more than 2000 people. The release could have been prevented if the Flare system had not been out of commission for extended maintenance or the Scrubbing system had been effectively
maintained. In both these examples the original HAZOP report would not have revealed the shortcomings that were present in the operating and maintenance standards on the plants.

The Process Industry recognised the limitations of design stage hazard studies during the 1990’s and some companies introduced standards for the periodic assessment of process related hazards. The need for such safety assurance standards was strengthened by legislative requirements under the OSHA 1910 PSM standard in the USA and the ‘Seveso II’ Directive in Europe. PSM calls for a hazard evaluation of all plants with significant quantities of highly hazardous chemicals that must be updated and revalidated at least every 5 years.

Under the ‘Seveso II’ Directive site operators with quantities of dangerous substances above specified thresholds need to demonstrate that all the major accident hazards have been identified. Furthermore, all measures necessary must be taken to prevent these accidents occurring and to limit the potential for harm to people and the environment. As with PSM, the Directive requires periodic re-assessment of major accident hazards every 5 years.

The need for continuous improvement in process safety, health and environmental (SHE) performance is illustrated in figure 1. The model suggests that after an initial learning phase when performance improves there is a tendency for decline if no action is taken to reverse this trend. The decline in performance is set against rising standards expected by employees, the local community and the regulators. It is argued that periodic safety assurance studies are necessary to maintain a continuous improvement in safety performance throughout the lifecycle of the plant that is at least ahead of stakeholder expectations.

There are a number of factors contributing to the potential for decline in safety performance on existing plants. The condition of plant equipment is deteriorating and after 10-15 years it is likely that some items will be reaching their expected design life, for example pipework subject to corrosion. Modifications to the plant will have been carried out and whilst each may have been separately assessed the resulting ‘creeping change’ may not have been adequately considered. Reduction in the level of operating personnel and supervision may well have taken place without proper consideration of the ability to respond in a crisis. The understanding of process hazards may also have been lost as new staff who were not involved in the original design or commissioning of the plant are recruited. It is also possible that design information has been lost or key design documentation is not kept up-to-date.

**Figure 1: Decline in SHE performance**

The need for continuous improvement in process safety, health and environmental (SHE) performance is illustrated in figure 1. The model suggests that after an initial learning phase when performance improves there is a tendency for decline if no action is taken to reverse this trend. The decline in performance is set against rising standards expected by employees, the local community and the regulators. It is argued that periodic safety assurance studies are necessary to maintain a continuous improvement in safety performance throughout the lifecycle of the plant that is at least ahead of stakeholder expectations.

There are a number of factors contributing to the potential for decline in safety performance on existing plants. The condition of plant equipment is deteriorating and after 10-15 years it is likely that some items will be reaching their expected design life, for example pipework subject to corrosion. Modifications to the plant will have been carried out and whilst each may have been separately assessed the resulting ‘creeping change’ may not have been adequately considered. Reduction in the level of operating personnel and supervision may well have taken place without proper consideration of the ability to respond in a crisis. The understanding of process hazards may also have been lost as new staff who were not involved in the original design or commissioning of the plant are recruited. It is also possible that design information has been lost or key design documentation is not kept up-to-date.
Development of PHR

It is unfortunately the case that serious accidents are often the catalyst for change within a company. In the late 1980’s ICI had many plants more than 20 years old [Ref. 1]. There was concern in the company that older plants had not been properly studied using HAZOP and that serious process related accidents were potentially waiting to happen. Then in 1987 a major fire occurred during start-up due to overfilling of a distillation column and flare knock-out pot. This was followed in 1989 by catastrophic rupture of a liquid ammonia pump on a Urea plant that killed two people in the machine house. These events gave urgency to the process that had already started, the systematic review of process hazards on all ICI plants worldwide.

The ICI Central Safety department issued a directive for safety assurance that included requirements for the identification of hazards, ensuring that appropriate equipment and facilities are provided to reduce risks as far as reasonably practicable and providing suitable systems and procedures. A small multi-disciplinary team met on the Urea plant where the fatal incident occurred to review process hazards over a 5-day period, raising a number of concerns unrelated to the accident. This formed the basis for the PHR technique that was refined during pilot studies of 12 further plants in the following year.

Key objectives in the development of PHR were to produce a time efficient methodology that addressed genuine safety concerns on the plant, taking into account the operating and maintenance experience and leading to a set of realistic improvement actions. Research on accident databases revealed that practically all process related accidents involved a ‘loss of containment’ at some stage during escalation of an event. At the heart of the method is a set of guidewords based on real-life accidents covering the full range of mechanisms for ‘loss of containment’. The main guideword headings are shown in table 1, these are supported by detailed prompts.

<table>
<thead>
<tr>
<th>Internal Explosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction Runaway</td>
</tr>
<tr>
<td>Overpressure</td>
</tr>
<tr>
<td>Extreme Temperature</td>
</tr>
<tr>
<td>Impact Damage</td>
</tr>
<tr>
<td>Excess Loading</td>
</tr>
<tr>
<td>Long Term Weakening</td>
</tr>
<tr>
<td>Loss via Opening</td>
</tr>
<tr>
<td>Leak</td>
</tr>
</tbody>
</table>

Table 1: Main PHR Guideword Headings

Each unit operation on a plant is reviewed in turn, allowing much quicker progress than the line-by-line approach with HAZOP. When reviewing a distillation system for example, the column, reboiler, condenser, reflux drum and other associated equipment would be considered as a single system. This approach allows hazards on the whole system to be overviewed and has been found to improve the ability of the team to identify major accident hazards.

PHR Methodology

To ensure an effective outcome it is essential that a suitable team is involved in the review. This needs to include operations and maintenance staff with direct experience of the plant plus technical experts on the process technology/chemistry and control system. A process safety specialist with suitable training and experience is required to facilitate the review, ideally this person should be independent from the plant to allow a fresh and unbiased perspective.
The first stage of the review is a scope meeting with the objective of setting a common understanding of the key issues to be considered, the main headings being:

- Brief history of the plant to be reviewed
- Unit operations to be included or excluded
- Dangerous substances and their hazardous properties
- Significant consequences and existing mitigation systems
- Vulnerable locations on site and in adjacent community
- Potential for external impact on plant, e.g. flooding
- Review of process related incidents on the plant

A majority of the review is involved with consideration of each unit operation using a structured hazard identification and assessment process. Firstly the process is described giving the main operating parameters, how the process is controlled and for batch processes the main steps in the operating sequence. Each ‘loss of containment’ guideword shown in table 1 is then considered to identify potential hazardous event scenarios. The worst credible consequences of the event are assessed and if judged to be a significant hazard the existing measures to prevent and mitigate are identified. The critical step in the review is for the team to decide whether these measures are suitable and sufficient and hence whether further measures need to be considered.

Recommendations at this stage typically fall into the following categories:

- Lack of information on the process or hazards requiring further analysis
- Further protective measures required to meet current standards
- Need for review of critical operating and maintenance procedures
- Need for design review of critical protective systems
- Quantification of event severity or likelihood required

During the review the team undertakes regular plant tours. The objective of the tour is to observe at first hand the issues from the hazard identification sessions and to form an overall view of the standard of operation. Some hazards are most easily seen on the plant such as the potential for vehicle impact with critical plant items. There is also an opportunity to check if critical safety systems are being correctly used. For example, are padlocks missing from ‘locked closed’ valves or isolation valves on pressure relief systems closed?

The outcome of the review is recorded on a standard form with a row for each hazardous event scenario including columns for the causes of ‘loss of containment’, the worst-case consequences in terms of harm to people or the environment, the existing prevention and mitigation measures and team recommendations for further measures.

The final stage of the review is a risk-based prioritisation of the recommendations using a calibrated risk matrix. Expert team judgement under the guidance of the leader is used to categorise the hazardous event severity and likelihood taking into account the existing protective measures. The event is then positioned on the risk matrix and the residual risk categorised from ‘Very Low’ to ‘High’. Prioritising recommendations in this manner has proved useful in allowing a staged approach for the resolution of actions and in deciding whether the investment in further measures can be justified.

Figure 2 shows the results from a review of a batch fine chemical manufacturing plant with hazardous events plotted on a risk matrix. This gives a visual profile of the risks on the plant and can be compared with other plants within the company to indicate comparative levels of risk and when deciding how to prioritise resources for improvement. On this plant there are a number of events in the ‘high’ risk category that require urgent attention to reduce the level of risk.
Consideration of Human Factors

The number of accidents in the Process Industry has reduced considerably since the early pioneering days mainly due to improved engineering standards and the reliability of equipment systems. To achieve continued improvements in safety performance the focus has now turned to the human causes of accidents. It is estimated that up to 80% of accidents are caused by the actions or omissions of people. Although the individual directly involved is often blamed for these accidents, for process plants it is more profitable to investigate failures in the layers of defence within the plant equipment and safety management system. A technique such as PHR provides the opportunity to proactively seek out weaknesses in these layers of defence in order to prevent accidents occurring.

When carrying out a PHR it is assumed that any credible human error will occur at some stage on the plant no matter how well the individual is trained and committed to safety. The focus of the discussions is then to assess the potential severity of the resulting accident assuming that any active defensive layers are unsuccessful in preventing the accident. For significant safety hazards it is important to establish that sufficient layers of protection are in place to prevent a single error leading to disaster. Additionally, the likelihood for the error is assessed to ensure that staff are not being ‘set-up’ to make an error due to poor training or job design. PHR utilises the experience of staff at the sharp end of plant operations. These operations and maintenance staff may well have witnessed minor incidents or near misses and this experience is backed by the human factors expertise of safety professionals on the team.
The loss of containment guidewords and prompts used for PHR include causes due to both equipment failures and human errors, examples of the latter include:

- Missed operation to inertise equipment
- Wrong drum of reactant taken from store
- Mal-adjustment of pressure regulator
- Vehicle impact with vulnerable equipment
- Road tanker driven away with hose connected
- Drain valve left open
- Valve to wrong storage tank opened
- Poor assembly of equipment leaving loose joints

As well as directly causing loss of containment events, people play a key role in responding to plant upsets and mitigating the effects of releases. When assessing the reliability of existing protective measures during a PHR, the factors affecting successful human intervention are considered in the same manner as actions taken by automatic systems such as plant trips or relief valves.

PHR recommendations generally identify areas of concern on the plant where new procedures need to be developed or the existing procedures need to be reviewed. In addition there are likely to be specific actions highlighted to reduce the likelihood of specific errors or to mitigate the consequences of an error. In high-risk situations where safety is dependent on a critical operating or maintenance procedure, an in-depth Human Reliability Assessment (HRA) may be required. This will consider a wide range of job design, individual and management factors that influence the likelihood for human error and make recommendations for improvements to reduce the risk of error to as low as reasonably practicable.

**PHR Experience**

Originally developed for continuous plants with large inventories of dangerous substances, PHR has now been successfully applied to a wide range of processes including oil and gas facilities, multistage batch plants in the fine chemical and pharmaceutical sectors, nuclear plants, pilot plants and large storage facilities. In fact, anywhere that a ‘loss of containment’ could lead to significant consequences the generic guidewords have proven to be effective. Common feedback from teams, especially plant operating staff, is that the process allows them to share their experiences on the plant more effectively than with other similar hazard identification techniques.

PHR has been used on almost 200 process plants worldwide and throughout this period has undergone continuous development and refinement. In the UK it has been used extensively in the last few years for the predictive aspects of safety reports required under the COMAH Regulations (implementing the ‘Seveso II’ Directive) and has recently been updated based on the experience gained. The well structured approach and linkage of major accident hazard scenarios with protective measures has been well received by the UK regulatory authorities.

Recommendations from reviews have a bias towards design checks and procedural improvements rather than hardware changes, reflecting the high cost of change on existing plants. This is a benefit when compared to applying HAZOP retrospectively as the focus is then towards hardware improvements as if the plant were still at the design stage.

Regardless of the process type, the following examples are typical of the recommendations raised during a PHR:

- Investigate the nature of the process hazard, e.g. potential for reaction runaway, electrostatic hazard of materials handled
Loss Prevention and Safety Promotion in the Process Industries
11th International Symposium Loss Prevention 2004 Praha Congress Centre 31 May – 3 June 2004

- Improve procedures for the management of ‘open ends’, e.g. drains, vents, sample points or road tanker connections
- Review the testing and inspection arrangements for critical equipment, e.g. relief valves, trip systems, vessels and pipelines
- Check the sizing of safety systems against latest methods, e.g. sizing of relief streams for 2-phase flow or where the discharge pipework has been modified
- Check the integrity of safety instrumented systems against the latest international standards
- Carry out a Human Reliability Assessment for critical operations to reduce the potential for human error
- Remove obsolete equipment to reduce the potential for leaks
- Provide crash protection for vulnerable equipment items
- Provide improved containment of spills to mitigate environmental effects

Natural Gas Terminal

PHR was chosen for a safety review of a large natural gas and condensate separation and treatment terminal in Europe, comprising ten processing and separation units taking gas/condensate from three separate sub-ocean gas gathering pipelines, condensate storage and loading facilities. The units were of various ages from two to twenty years old. The review was completed over a 10-week period from initial discussions through to presentation of the final report with the key activity during a four-week period with approximately 10 half-day team meetings.

The report allowed the company's management to target resources onto the highest priority process safety issues and provided a clear view of the status of the whole site on a coherent basis for the first time. This was essential before further development could be planned for the site and a strategic direction for its future growth put in place.

The use of PHR was quite novel to the company but was judged to be completely successful in achieving its’ objectives. The alternative under consideration was to carry out a retrospective HAZOP on the plant that would have taken many months to complete and was not viable because resources to man such a study were not available.

Batch Pharmaceutical Plant

A pharmaceutical site in the UK was required to carry out a process risk assessment under the COMAH Regulations and was struggling with how to cover all plants within the time available. A suitable methodology was developed based on PHR and building in parent company requirements. A pilot study was carried out on a multi-stage batch pharmaceutical intermediate plant with 6 process steps including high-pressure hydrogenation. The plant handled hazardous substances such as flammable toluene and methanol plus toxic phosphorous oxy-chloride and ammonia solution. The review was carried out over a 2-week period and involved 6 half-day team meetings. A number of concerns were raised including:

- Improved understanding of DCS based interlocks
- Assessment of explosion risk during charging of flammable dusts via manway
- Reaction runaway hazards with addition of wrong materials
- Assessment of anti-static measures with handling of toluene
- Release of pressure from hydrogenation vessel into vent system

Following the successful pilot study local process safety resources were trained to lead a series of further risk assessments across the site, completed within a 6 month timescale and in time for successful submission of the site safety report.
Periodic Reviews

Many of the plants originally reviewed using PHR in the early 1990’s have required further reviews based on the 5 year cycle stated in legislative and company requirements. The objective for periodic reviews is to achieve continuous improvement in process safety performance, learning from experiences on the plant, building in improved standards where beneficial and continuously looking for ways to reduce the overall risk profile for the plant.

It is normally inappropriate to fully repeat the PHR exercise unless the plant has been significantly altered. A technique known as PHR Round 2 has been developed that typically requires a half of the time required for a full PHR. Each of the unit operations are considered and the following questions posed to a team of experienced staff:

- Have the recommendations from the original PHR been completed and have these achieved the expected results
- What changes to plant hardware, software, manning levels, etc, have been carried out since the original review and have the potential effects been adequately considered
- Have significant process related incidents occurred and have these been adequately investigated to identify the root causes and improvements implemented to prevent a re-occurrence
- Is the team happy that the original review covered the key hazards on this unit operation and is further hazard identification required

Operational Hazard Review (OHR)

PHR was developed for the process industry where the handling of significant inventories of dangerous substances creates the potential for ‘loss of containment’ leading to fires, explosions, toxic releases, health effects or harm to the environment. The process industry along with the rest of the manufacturing sector exposes workers to a much wider range of hazards during their work. For example, falls from height, exposure to high noise levels or the hazards associated with moving machinery and workplace transport. To provide companies with a generic risk assessment process for the workplace the Operational Hazard Review (OHR) technique has been developed. This shares many aspects of the approach for PHR including the high level identification of significant safety concerns and the creation of a targeted risk based improvement plan.

<table>
<thead>
<tr>
<th>Hazardous substances</th>
<th>Combustible materials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flammable liquid</td>
</tr>
<tr>
<td></td>
<td>Flammable gas/mist/dust</td>
</tr>
<tr>
<td></td>
<td>Reactive substances</td>
</tr>
<tr>
<td></td>
<td>Acute toxic substances</td>
</tr>
<tr>
<td></td>
<td>Chronic toxic substances</td>
</tr>
<tr>
<td></td>
<td>Radiation</td>
</tr>
<tr>
<td></td>
<td>Eco-toxic substances</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Release of Energy</th>
<th>Equipment rupture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Moving Machinery</td>
</tr>
<tr>
<td></td>
<td>Flying/Falling objects</td>
</tr>
<tr>
<td></td>
<td>Workplace Transport</td>
</tr>
<tr>
<td></td>
<td>Electricity</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Workplace Hazards</th>
<th>Thermal burns</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Noise</td>
</tr>
<tr>
<td></td>
<td>Vibration</td>
</tr>
<tr>
<td></td>
<td>Manual Handling</td>
</tr>
<tr>
<td></td>
<td>Repetitive Tasks</td>
</tr>
<tr>
<td></td>
<td>Poor Posture</td>
</tr>
<tr>
<td></td>
<td>Slips/trips/falls</td>
</tr>
</tbody>
</table>

Table 2: OHR Hazards Guide Diagram
The manufacturing process is split into a number of discrete workstations and the guidewords in table 2 applied to identify potential hazards. The range of tasks carried out at this workstation is then considered to identify ways in which staff can be exposed to these hazards. For each credible hazardous event the likely consequences, existing protective measures and need for improvement actions are assessed. For example, in busy goods unloading areas within factories people walking through the area may be at risk of being hit and seriously injured by moving vehicles. The improvement action would ideally be to keep all non-essential staff out of the area but if this is not feasible then safe pedestrian routes should be marked out and people trained in their use.

The OHR technique has been used on a number of manufacturing sites and has been successful in ensuring that the full range of hazards have been considered. The output from the review allows companies to demonstrate that they have taken all necessary measures to reduce risks to their employees to as low as reasonably practicable.

**Environmental Hazard Review (EHR)**

Under new legislation or as the result of incidents on their plants, many companies need to carry out risk assessments on the environmental impact from accidental releases. The Environmental Hazard Review (EHR) technique has been developed from PHR to allow a rapid review of environmental hazards on a plant or site.

Once again the potential for ‘loss of containment’ is a prerequisite for harm to occur but for an EHR the safety implications of such releases need not be assessed. The technique uses the source-pathway-receptor model for environmental incidents. The source is the ‘loss of containment’ event such as pipe rupture, joint leak, tank overfill, etc, the pathway is the route taken by the pollutant via air, water or ground, and the receptor is the part of the environment that could be harmed by the release.

In the first stage of the review the eco-toxic properties of the substances handled on the site are assessed along with the sensitive environmental receptors around the site. Based on the inventories of hazardous substances held on the site credible incidents causing significant environmental damage are identified. At this stage a number of low impact hazards may be screened out to allow efforts to be focused on a smaller number of high-risk events.

A pathway analysis is carried out to identify routes by which releases of hazardous substances can reach the environmental receptors of concern. Mitigation measures on these pathways are assessed for their reliability, for example bunds on tanks, isolation valves on drains and spray curtains for containing releases of toxic fumes.

In the final stage of the review all significant inventories of hazardous substances are considered. Mechanisms for ‘loss of containment’ are identified using a guide diagram and the range of consequences assessed with reference to the pathway analysis and sensitive receptors. Although improvements to reduce the likelihood of ‘loss of containment’ may be appropriate, EHR pays particular attention to the mitigation measures on pathways. In many cases it may be possible to prevent significant environmental harm by providing improved containment for leaks.

**Conclusions**

The PHR technique described in this paper has been shown to be highly suitable for carrying out retrospective safety assurance reviews on existing plants. It has provided a time efficient and effective technique to allow companies to meet their obligations for continuous improvement in process safety. The benefits of PHR are summarised below:

- Time efficient compared to techniques such as retrospective HAZOP
- The process encourages the active participation of operating staff
Efforts are focussed towards significant process safety risks
Suitable consideration is given to human factors in accident causation and mitigation
The review helps to build a corporate and plant knowledge base
The review provides the basis for a prioritised improvement plan
The method is proven across the process industry and has been accepted by the regulators

Recent development of PHR to encompass Operational Hazard Review and Environmental Hazard Review, now provides a suite of tools that can be applied across the manufacturing sector. These techniques can help to ensure that risks have been reduced as far as reasonably practicable thereby enabling a demonstration to be made that all measures necessary are being taken to avoid harm to people and the environment.

References