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The Changing Face of HAZOP

An ioMosaic White Paper

Abstract

This paper considers changes in Hazard and Operability (HAZOP) methodology since its introduction 40 years ago. HAZOP is a team-based activity for identifying process hazards and operability concerns. The intent is to review process design and identify hazardous deviations through facilitated application of guidewords, then evaluate safeguards and (where necessary) recommend improvements.

HAZOP's origins are well documented, originally in the UK at Imperial Chemical Industries (ICI) and Chemical Industries Association (CIA) and then codified within the Institution of Chemical Engineers (IChemE) guidelines. The technique was subsequently adopted by the American Institute of Chemical Engineers (AIChE) and endorsed within US Occupational Safety and Health Administration (OSHA) Process Safety Management Regulations, where HAZOP is identified as a preferred method of Process Hazard Analysis (PHA).

The original HAZOP concept was comparatively simple, comprising structured brainstorming of high-hazard processes within the chemical industry. HAZOP activities were generally in-house, operator-led and largely collaborative team activities. Discussion and recording of identified hazards was often 'by exception', with only notable issues identified and recorded.

By contrast, HAZOP now has near-universal application within process, energy, transport and utilities industries. HAZOP methodology and content have also increased significantly. HAZOP is now typically independently facilitated with multiple participant stakeholders (e.g. project or process owner, operator, contractor, consultant, etc.). Discussion and full recording, based on a complete set of guide words, is universally required.

Another significant change is the extent to which risk assessment is applied within HAZOP. Starting with simple classification of findings and recommendations, this methodology has progressed through generalised risk ranking of all HAZOP recommendations and latterly to using risk-based decision criteria.

Where dedicated Safety Instrumented Systems (SIS) are included for process safeguarding, their functional integrity is also studied more formally using Layer of Protection Analysis (LOPA) and Safety Integrity Level (SIL) classification. These activities are often performed in conjunction with, or immediately following, a HAZOP.

Other practical and logistical challenges result from the introduction of computer and projection technology and bespoke HAZOP software applications. Although these bring undoubted real and

potential benefits in terms of transparency, consistency and team engagement, they can become a distraction if not properly managed.

Finally, the increasing demands of methodology, stakeholder engagement and embedded risk analysis are not always recognised within project schedules. This can lead to commercial and technical pressures and conflicts. Careful balancing of technical, quality and commercial goals has therefore become increasingly important.

In summary, HAZOP remains a unique and valuable element of effective process safety management. Ongoing challenges include increasingly complex methodology, study timeframes and increased application of embedded risk assessment. Whilst these evident pressures require careful balancing of work scope, study participation and output quality, HAZOP remains an international methodology of choice for designers, operators and regulators, within a diverse range of industry applications.

Keywords: Hazard & Operability, HAZOP, Hazard Identification, Risk Management, Safety Management .

Background and History

Major accidents such as Flixborough and Bhopal catalysed process safety management systems and legislation within the United States and Europe.

1.1 Europe

The Flixborough accident was an explosion at the Nypro Ltd site near Flixborough, England on 1 June 1974. An accidental release of cyclohexane resulted in a vapor cloud explosion that caused 28 fatalities.

The Seveso disaster was an incident that resulted from an exothermal decomposition reaction occurring at the Industrie Chimiche Meda Società factory in northern Italy on 10 July 1976. The runaway reaction caused contamination of almost 2,000 hectares of land and deaths of more than 70,000 animals.

After these incidents, the Health & Safety Executive (HSE) assembled a committee of experts, the Advisory Committee on Major Hazards (ACMH) to study hazard management and policy making. Later, the Commission of the European Communities (CEC) introduced series of directives for the control of industrial hazards. Specifically, the European Commission set out requirements in "Seveso II" Directive (96/82/EC) concerning a "Major Accident Prevention Policy" and "Safety Management Systems (SMS)".

1.2 USA

The Bhopal accident was another critical turning point in the process safety industry. On 3 December 1984, large quantities of methyl isocyanates escaped a storage tank and formed a toxic gas cloud at the Union Carbide India Limited plant, killing thousands and injuring hundreds of thousands of people.

After Bhopal and other serious chemical accidents that occurred throughout the late 1980s internationally as well as domestically, the US Environmental Protection Agency (EPA) initiated several programs to promote hazard identification and information sharing and emergency planning. In the 1990s, Congress published the Clean Air Act (CAA). Requested by Section 304 of the CAA Amendments of 1990, the Occupational Safety and Health Administration (OSHA) developed the Process Safety Management (PSM) regulations to manage reporting from facilities that have specified hazardous chemicals above certain threshold quantities. The regulations were enacted in 1992. The EPA also promulgated the Risk Management Program (RMP) regulations based on Section 112 of the CAA Amendments.

Process Safety Management (PSM) is a framework for managing integrity of systems and processes handling hazardous substances. As indicated in the table below, hazard identification and process hazard analyses are identified as a key element with PSM and also the equivalent European safety management system frameworks.

Table 1: Elements in OSHA PSM and Seveso II SMS

USA OSHA – Process Safety Management Elements	Europe/UK CEC SEVESO II - Safety Management Systems Elements
1. Employee Participation 2. Process Safety Information **3. Process Hazard Analysis (PHA)** 4. Operating Procedures 5. Training 6. Contractor Safety 7. Pre-Startup Safety Review 8. Mechanical Integrity 9. Hot Work Program 10. Management of Change 11. Incident Investigation 12. Emergency Planning & Response 13. Compliance Audits 14. Trade Secrets	1. Organization and Personnel **2. Hazard Identification and Evaluation** 3. Operational Control 4. Management of Change 5. Planning for Emergencies 6. Monitoring Performance 7. Audit and Review

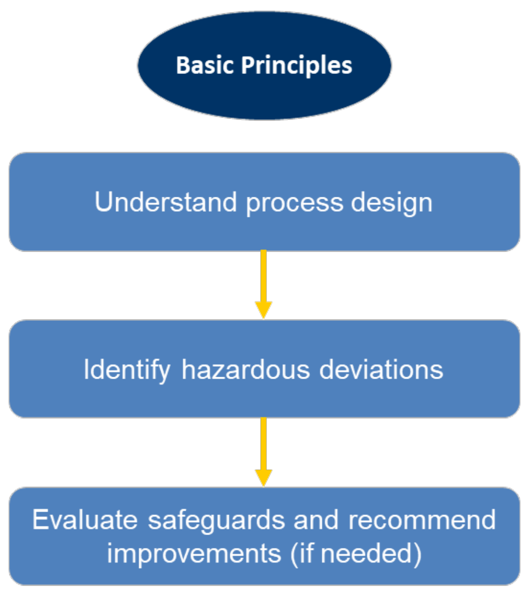
Source: OSHA, EU/EC

HAZOP Technique Overview

Hazard & Operability (HAZOP) is a structured hazard identification method. The technique originated from work conducted by ICI in the 1960s, culminating in the publication of a Guide to Best Practice by the UK Chemical Industries Association (CIA) in 1977. In 1985, the Centre for Chemical Process Safety (CCPS) under AIChE established published its first project "Guidelines for Hazard Evaluation Procedure" in 1985. In 1992, OSHA identified HAZOP as a preferred method for PHA study under CFR 1910.119.

A HAZOP study is completed by facilitated team discussion of potential undesirable events that may create hazards or operability problems. Study outcomes are recorded on HAZOP worksheets. A flowchart of its basic technical and managerial principles can be found in Figure 2 Basic HAZOP Workflow. The 3 main steps are: to understand process design, to identify hazardous deviations, and to evaluate safeguards and recommend improvements.

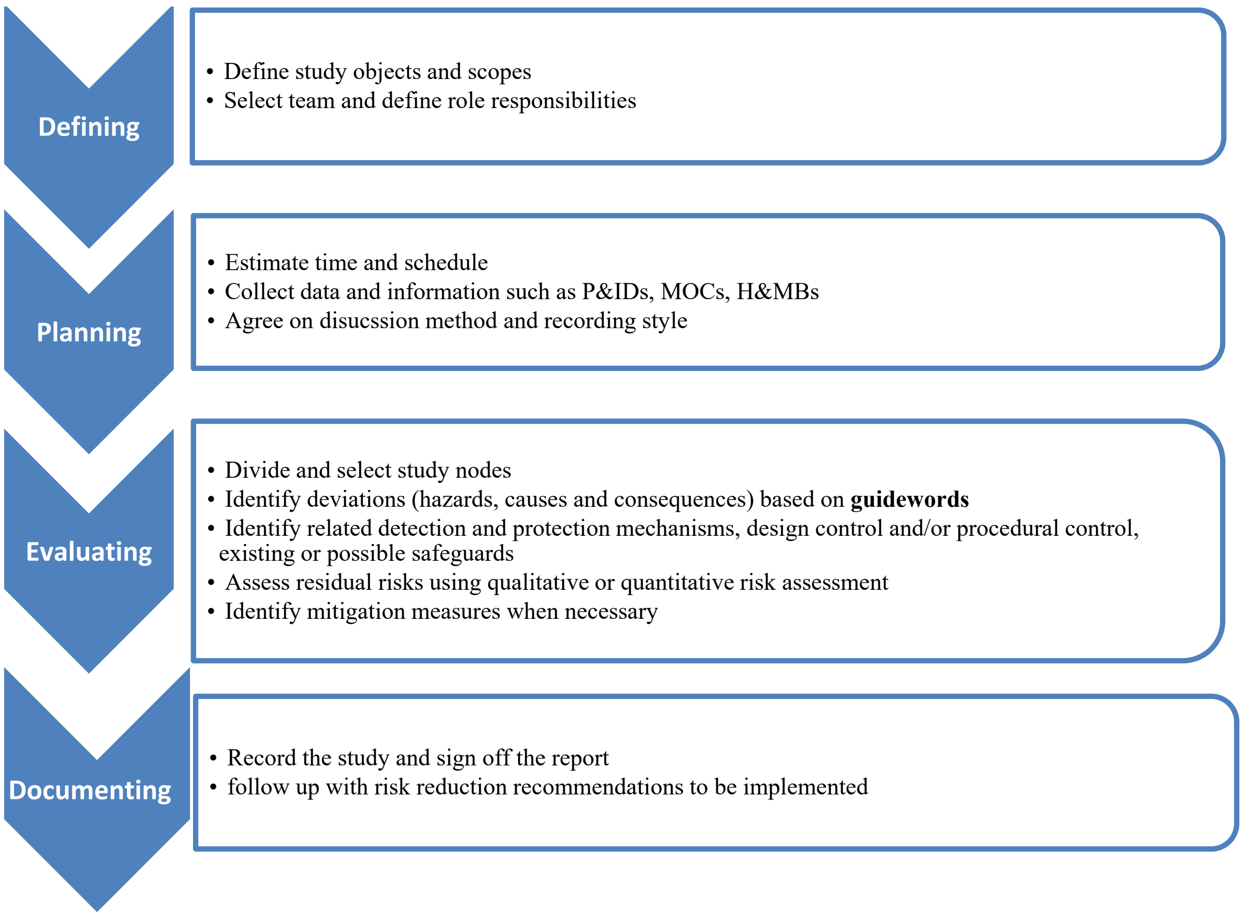
Figure 1: Basic HAZOP Principles



Source: ioMosaic Corporation

Successful execution of the method may follow the basic process below in Figure 2:

Figure 2: Basic HAZOP Workflow



Source: ioMosaic Corporation

Changing Factors in the HAZOP Evolution Blueprint

A successful HAZOP study requires concerted efforts from an experienced team in order to:

- Deliver an Inherently Safe Design (ISD) that prioritises elimination of risk over other mitigation approaches
- Reduce hazard likelihood using possible feasible prevention measures
- Reduce hazard consequences using selective mitigation measures

3.1 Application Change: From Chemical Industry to a Variety of Industries

HAZOP was originally designed to identify hazards present in chemical facilities that handle highly hazardous materials. HAZOP's application has subsequently been extended to food safety, medical, transportation industries. Due to the increasing complexity of processes and advance in technologies, HAZOP has also evolved to adapt changes in hazard identification and loss prevention methods and applications in wide range of various industries.

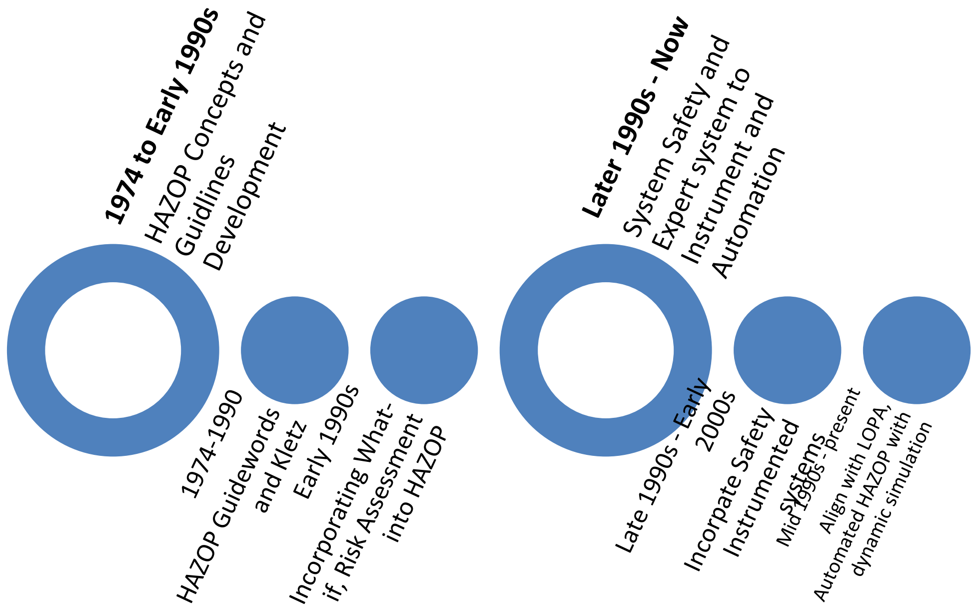
3.2 Concept Change: Concepts Have Advanced from Simple to Complicated

The original concept of HAZOP was to identify deviation from the design intent following physical equipment-based and process-oriented examination techniques.

Prior to the 1990s, many published literature focused on principles and factors that need to be taken into consideration in regards of technical, operability and managerial aspects. Later, Suokas & Rouhiainen (1989) proposed that all practitioners should incorporate organizational management systems as a standardised element in HAZOP studies. With further investigations into root analysis for industrial incidents, researchers realised accidents could be prevented by in-time and correct human responses. Human errors result in 50 to 90 percent of operational risks (Baybutt, 2002). The scope of HAZOP has therefore expanded to include analysis consequences of human errors. Schurman and Fleger (1994) introduced a set of guide words and parameters to evaluate operator actions, administrative procedures and adequate training to limit potential risks. From the mid-1990s onwards, there has been increasing interest in computer-automated HAZOP and simulation of the possible solution to hazards.

The following Figure 3 depicts the interests of general research papers over the past 40 years.

Figure 3: Trend in Literature Review on HAZOP Studies



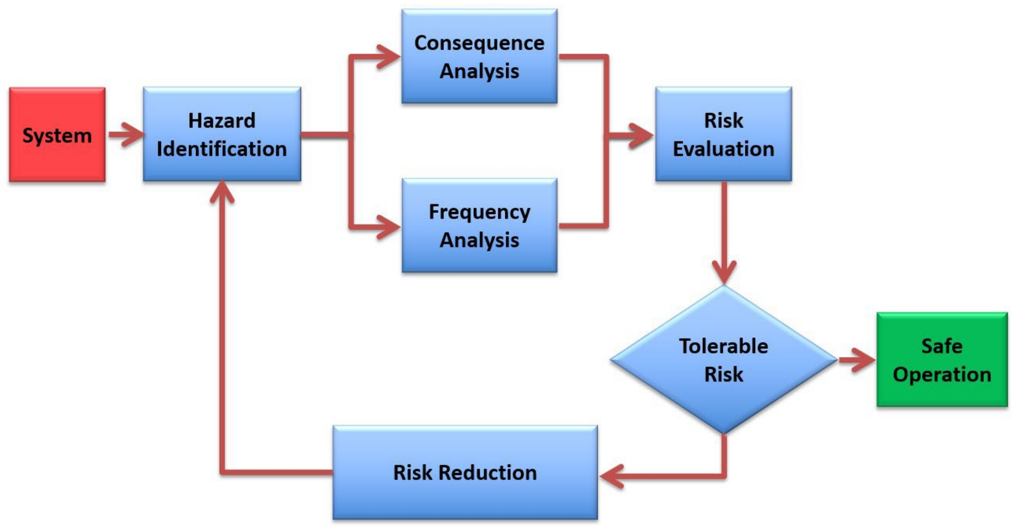
Source: ioMosaic Corporation

3.3 Methodology Change:

3.3.1 Risk Evaluation is increasingly applied in HAZOP

Risk assessment provides qualitative or quantitative evaluation of a range of possible safety and health consequences. Possible scenarios of undesired events and potential hazards are evaluated as a function of consequence analysis and likelihood analysis. The following workflow indicates how risk analysis can be incorporated alongside hazard identification techniques.

Figure 4: Risk-based Hazard Identification Workflow



Source: ioMosaic Corporation

For existing designs, consequence severity analysis should consider initial and any escalated effects. The level of effort required for a consequence analysis is based on the number of loss of containment events and the associated failure scenarios. It is important to consider impacts on safety, the environmental and economic operations including loss of production and equipment damages. The categories may not be identical among companies depending on company acceptance of risk and the regulations with which they comply. Since consequence severity is often used to screen potential events, it is important to document the ranking without consideration of any safeguards or administrative control activities. Table 2 provides an example set of consequence categories for an industrial facility.

Table 2: Example Consequence Criteria – Without Mitigation

SEVERITY	SAFETY	ENVIRONMENTAL	ECONOMIC
1	Minor injury or health impact	Small release, non-reportable	< $10 k
2	Injury requiring medical treatment	Non-reportable release with onsite cleanup	$10k - $100k
3	Lost time injury	Reportable release with no offsite impact	$100k - $1M
4	Onsite fatality or severe injury Public injury	Reportable release with offsite impact and cleanup	$1M - $10M
5	2 or more onsite fatalities Public fatality	Reportable release with permanent offsite environmental damage	$10M +

Source: CCPS

Likelihood of occurrence analysis evaluates the likelihood of occurrence of hazardous scenarios identified during a HAZOP based on experience, existing safeguards and extrapolation from historical accident data. Appropriate probabilistic mathematics techniques such as Fault Tree Analysis (FTA) can be used to determine the frequency estimates. Selection of models, assumptions and data should be reviewed carefully based on team experience and judgment. Table 3 illustrates an example of a likelihood ranking set.

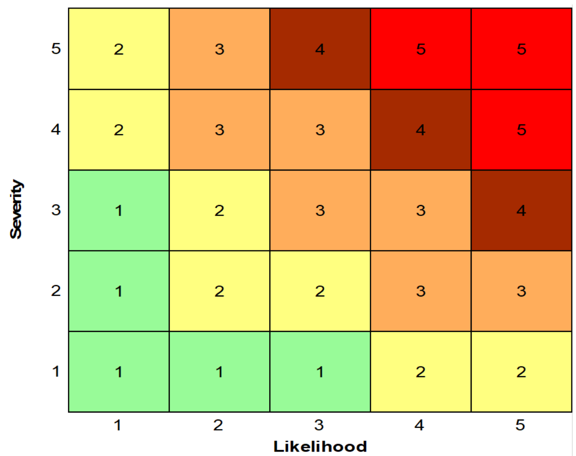
Table 3: Example Likelihood Criteria – With existing safeguards

LIKELIHOOD	DESCRIPTION & STATISTIC
1	Highly unlikely, but heard of in industry - 1 in 10000 yrs
2	Remote chance it could occur - 1 in 1000 yrs
3	Could occur during facility lifetime - 1 in 100 yrs
4	Likely to occur more than once during facility lifetime - 1 in 10 yrs
5	Relatively frequent occurrence - 1 in 1 yr

Source: CCPS

A risk matrix indicates residual risk acceptability and risk reduction requirements. Risk levels can be used to determine which scenarios are undesirable, which scenarios are marginal and which scenarios are critical and require additional mitigation. Companies may develop specific requirements and rankings in order to prioritize hazards and risk reduction strategies. Figure 5 presents an example of a risk matrix used at a facility during a HAZOP.

Figure 5: Risk Matrix



Source: CCPS

3.3.2 HAZOP Study Links Automation, Functional Safety and Multiple Hazard Identification Methods

HAZOP has further evolved to consider dynamic simulation and programmable automated systems. Automated process requires assignment of a target SIL for SIS safeguards in order to safely control a process in the event of upset.

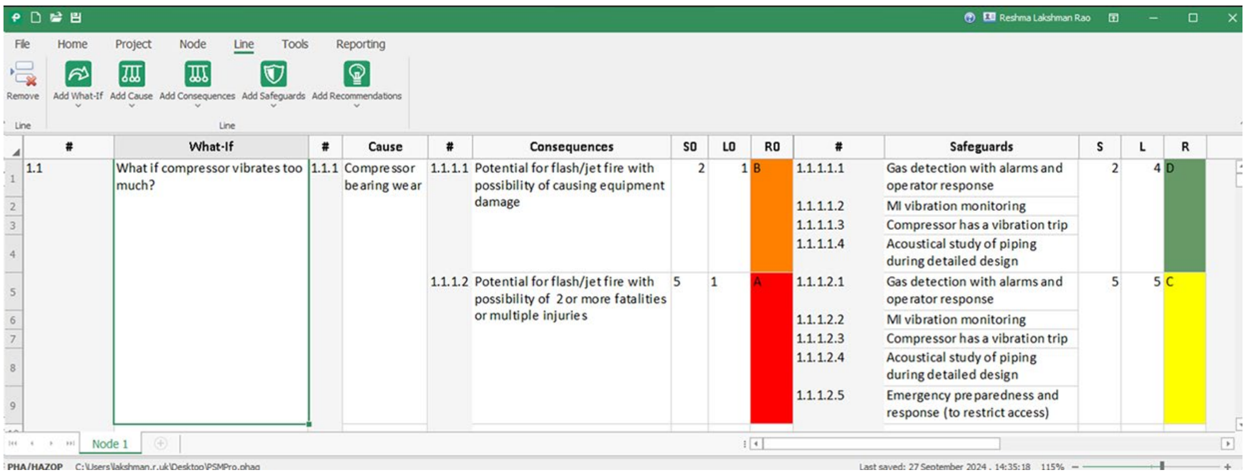
Summers' team and Dowell III's team studied HAZOP as a tool fulfilling some requirements for functional safety and LOPA (Summers 1998, Dowell III 2005).

HAZOP started as a systematic labor-intensive activity that could be time-consuming. Automated HAZOP systems the reduce this effort have been proposed since the mid-1990s. There is also continued interest in combining dynamic process simulations with HAZOP studies, both for training and process monitoring and record-keeping purposes. Dynamic simulation helps optimized solutions for identified hazards.

For example, to offset limitations of a single technique, two or more hazard identification methods could be incorporated alongside HAZOP – for example Quantitative Risk Analysis (QRA) and Failure Mode and Effect Analysis (FEMA).

Software tools such as Process Safety Office® PSMPro™ can greatly assist with the efficiency of HAZOP studies, Process Hazard Analysis (PHAs), Dust Hazard Analysis (DHAs), compliance audits, and fault trees.

Figure 6: PHA and LOPA Tool Example



Source: Process Safety Office® PSMPro™, ioMosaic Corporation

3.4 Study Schedule Adapts to Management of Change to Processes and Incidents

Successful completion of HAZOP relies on fulfilment of responsibilities and successful implementation of actions by each of the study team members throughout preparation, execution and documentation stage. Refer to Figure 7 for an example of some of the information gathered.

HAZOP may be performed at various points throughout a project development cycle from early concept design through FEED and prior to commissioning. Typically, the regulations require HAZOPs to be revalidated every five years. It is not unusual to find shortfalls in previous hazard studies, the conventional 5-year revalidation period may therefore be insufficient. Process changes during this period may introduce new hazards or, for previous studies, poor recommendation implementation may leave hazards unmitigated.

Companies should therefore develop a management system to organize, update and review knowledge periodically throughout a process's lifetime, including that appropriate documents such as as-built drawings and procedures are up to date. One way to minimize such inherent risk in hazard identification is to treat the HAZOP study as an 'evergreen' process, which will require the existing study to be updated after each incidents or near-miss, and to be updated as any recommended changes are reviewed and implemented with the guidance of standardized Management of Change (MOC) processes. Project managers may also audit to check the quality of input data or to confirm if process data are adequate. Audits might also include a review of agreed corrective actions to confirm scheduled implementation.

Figure 7: Summary of HAZOP Members Roles and Responsibilities

ROLE	HAZOP MANAGEMENT STAGE	HAZOP EXECUTION STAGE	HAZOP DOCUMENTATION STAGE
HAZOP manager has to ensure all study stages are carried out with success, having into account both company and legal requirements			
MANAGER	To define the purpose, scope and objectives of the study To select the team leader To select the expert team To provide the required documentation To communicate the study plan To guarantee the required HAZOP meeting room	To ensure the attainment of the study requirements To ensure the responsibilities assignment	To ensure the final documentation quality To follow-up the recommendations
Site Coordinator is an optional role intended to support the HAZOP manager for ensuring well-suited sitting facilities, locations, equipment, etc.			
COORDINATOR	Liaison between team and HAZOP meeting room	To manage the team inside the work place To facilitate any required photocopy, etc. To manage the lunch logistics, refreshments, etc.	-
Team Leader' role is based on guiding the whole HAZOP. It is recommended that the team leader is not directly related to the company with the aim to ensure objectivity.			
LEADER	To analyze the required HAZOP documentation To subdivide the system into nodes To plan the sequence of work sessions To know legal requisites To ensure the documentation quality, quantity and deadline	To define the study to the team To explain the HAZOP technique to the team To guide the team on during HAZOP sessions To ensure the effective work of the team To maintain the control of the sessions schedule	To carry out the final study report
Scribe is an optional role intended to support the team leader on all HAZOP stages and document the information generated during HAZOP sessions			
SCRIBE	To provide technical support to the team leader	To document the generated information during sessions	To provide technical support to the leader
Expert team is a multidisciplinary group of professionals with different background with the aim to ensure a thorough review of the process			
TEAM	To claim the documentation with sufficient prior notice To analyze in detail the documentation received To have knowledge of the process to be analyzed	To be involved on the hazard identification stage To identify causes and consequences of scenarios To identify process safeguards To propose recommendations	To check the final documentation To evaluate the labor of the team leader To focus on solving recommendations

Source: ioMosaic Corporation

Case Study: Industry Incidents Prompted Improvements in HAZOP

The major incidents mentioned previously in the 1970s and 1980s shaped the thinking of process safety management and helped develop various hazard identification methods, including HAZOP. These incidents also resulted in an increased awareness of the potential consequences of process safety hazards and highlighted limitations in HAZOP at that time. This section considers an example incident and highlights the benefits of effective HAZOP application.

4.1 Case Study: 2011 UK Chevron Pembroke Amine Regeneration Unit Explosion

An atmospheric storage tank in the Amine Regeneration Unit (ARU) at the Chevron Pembroke Refinery exploded on 2 June 2011. Four people died and a fifth was severely injured.

What went wrong 1:

Prior to the explosion, there were several notable events. In 1998, there was a process change to allow redirection of flare drum residue into the amine running tank. On 7 May 2004, a tank explosion and fire in a nearby unit triggered a site-wide review to identify LPG risk. Up to 2008, Chevron had incorrectly downgraded the hazardous area classification for ARU tanks from ‘high risk’ to ‘non hazardous’. The Health and Safety Executive (HSE) investigation report commented that the running tank headspace should have been identified as ‘Zone 0’ (highest risk).

What could an effective HAZOP do to prevent this?:

The incident investigation report of the 2011 explosion noted that Chevron’s safety information was inadequate, especially for the previous process alterations on the light hydrocarbon contamination hazard. This led to inaccurate hazardous zone classification. A robust HAZOP would have identified the causes and consequences of loss of containment and helped prevent this type of incident from occurring.

What went wrong 2:

The Chevron ARU process hazard and analysis and safety objective analysis (PHA/SOA) completed in February 2010, carried out by a team of eight, was not a meaningful risk assessment as the team did not sufficiently consider process hazards and they were not fully aware of all the relevant information.

What could an effective HAZOP do to prevent this?:

An effective HAZOP would have supported the revalidation of loss of containment events due to process change. Had the study team reviewed the system using combined HAZOP and LOPA, they could have analysed instrumentation reliabilities and human responsiveness, and thence take further corrective actions to prevent such an incident from happening. This incident acts as a reminder to those with the responsibility at corporations for employees, contractors and residents to proactively sustain risk evaluation, management and communication system to ensure the processes and workplaces are safe.

What went wrong 3:

Key operators were unaware of the existence of “lessons learned” reports from previous incidents and some operators considered the updated operational instructions were impractical to follow.

What could an effective HAZOP do to prevent this?:

Positive safety culture could have been enforced by providing effective administrative controls and adequate training. The HAZOP team could have considered human errors as well as organizational factors within the analysis.

Summary

Table 4 below is a summary of the evolutions in HAZOP studies.

Table 4: Trends in HAZOP – Changes in the details

Aspects	1970s to Early 1990s	Early 1990s to Present
Team Dynamics	▪ Typically operator led, in-house & collaborative team activity ▪ Limited session frequency and duration – To avoid team 'burnout'	▪ Typically independently facilitated, multiple participant stakeholders (owner, operator, contractor, consultant etc.) ▪ Continuous lengthy studies – Due to increased complexity & project schedule demands
Industry and Scope	▪ Brainstorming of selected high-hazard processes only ▪ Chemical industry focused	▪ Widespread, universal application to all significant processes ▪ General application throughout process and energy industries (also others)
Study Materials	▪ Hand-drafted P&IDs – Limiting number of drawings (but less consistent and sometimes 'crowded') ▪ Standalone control, alarm and interlock systems – basic redundancy architecture ▪ Hand-marked documents, handwritten study notes	▪ CAD drawings – More consistent, less crowded but many more ▪ Complex DCS, alarm and ESD systems – SIL and LOPA introduced from early 2000s ▪ Computer aided documentation, specialized HAZOP software
Team Style	▪ Discussion based – Focused on hard-copy drawings and offline reporting ▪ Recording 'by exception' – Only notable issues documented ▪ Design risk acceptability and recommendations based on team's 'expert judgement' ▪ Conceptual risk reduction recommendations – Subject to evaluation and design	▪ Online projection of study record – Subject to real-time team discussion and challenge ▪ Full recording – All guidewords documented, irrespective of hazards ▪ Design risk acceptability and recommendations require formal risk assessment ▪ Pressure to develop specific, actionable engineering recommendations

source: ioMosaic Corporation

Future Challenges

The ongoing challenges for keeping an up-to-date and effective HAZOP study include:

- Increasingly complex methodology places greater demands on the HAZOP team
- Tight study timeframes due to increased methodology complexity and overload of process and design information
- Application of risk criteria may not be interpreted the same way by different study teams
- Commercial pressures may sacrifice some extent of quality due to time deadlines and budget limitations
- Limitations of effectiveness – We must also keep in mind that HAZOP method may not be suitable for every stage of a process life cycle. The cost of modifying an existing process to an inherently safer process may be economically unfeasible.

Conclusion

Regulatory authorities clearly recognize hazard identification as a key element of safety management systems. Structured Hazard & Operability (HAZOP) studies are recognised as significantly contributing to this objective. Practitioners should be aware of the evolution of HAZOP, detailed methodologies and current limitations. Since HAZOPs are conducted by a team, it is subject to team members' experience, knowledge and bias. One should attempt to gain knowledge from expert personnel, as well as standardize the HAZOP structure for processes following industry guidelines and technology trends. Human factors, organizational factors and safety cultures have been attributed as a cause or partial cause of an incident; therefore, human errors should be considered as an initiating event or as a factor resulting into typical process deviations. When linking the HAZOP studies to programmable electronic systems such as SIL values, potential causes of instrumentation failures should not be ignored. The current HAZOP limitations and future challenges also call for further research to continuously improve HAZOP techniques and advanced technologies to reduce study time to increase efficiency. Finally, a combined HAZOP/LOPA study can help put a successful framework in place from basic planning to risk evaluation, and hence improve the quality of design and accomplish risk reduction and mitigations in hazardous processes.

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Additional Resources

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