International Journal of Engineering, Science and Mathematics
Vol. 7Issue 1, January2018,
ISSN: 2320-0294 Impact Factor: 6.765
Journal Homepage: http://www.ijesm.co.in, Email: ijesmj@gmail.com Double-Blind Peer Reviewed Refereed Open Access International Journal - Included in the International Serial Directories Indexed & Listed at: Ulrich's Periodicals Directory ©, U.S.A., Open J-Gage as well as in Cabell's Directories of Publishing Opportunities, U.S.A

Role of HAZOP in assessing risk of accidents in chemical process industries: capability and lacunae

by

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Abstract

Accidents in chemical process industries can not only cause losses of life and property but can alsoresult in irreparable and incalculable damage to the environment exceeding several billions of rupees. This is amply reflected in the Bhopal gas tragedy of 1984 and numerous accidents that have occurred across the world before or since. Such accidents also cause major losses of employment and shake the faith of people in industrial development. Hazard and operability (HAZOP) study is one of the seminal techniques for assessing risk of such accidents and prevent their occurrence. The present paper assesses the role of HAZOP and its capabilities. It then identifies the shortcomings that need to be addressed for achieving the HAZOP's true potential, and summarizes the attempts being made across the world to meet this challenge.

Keywords: Chemical process industry, accidents, risk, hazard and operability, HAZOP, process safety

1. Introduction

It was a sequence of human errors ─ all of which were easily avoidable ─ that had led to the accidental release of the lethal methyl iso-cyanate (MIC) gas from the factory of M/s Union Carbide Corporation (UCC) at Bhopal in December 1984 (Abbasi and Abbasi, 2005). The plume of about 45 tonnes of MIC that came out of the non-functioning flare tower of UCC that night killed or maimed over 20,000 persons. It also toxified large areas of land and water that remain as contaminated today as they had become 34 years ago and will perhaps never get detoxified. The accident also dealt a mortal blow to UCC which got shut for ever, throwing thousands of workers out of job.

Prior to the Bhopal gas tragedy there have been disasters like the one that occurred at Seveso in 1976 (Lees, 2005) which had threatened to make an entire town unhabitable by toxifying it with dioxin. And after the Bhopal gas tragedy, also, accidents have been occurring with similarly disastrous consequence. For example the Buncefield disaster of 2005 has caused estimated losses of US dollor 500 billion and the BPL refinery disaster of 2010 has harmed larger areas of marine environment than any other past accidenthas (Abbasi *et al.*, 2017 a,b; Tauseef *et al.*, 2017). Similar examples abound (Khan and Abbasi 1997a, b, c; 1998 a, b, c, d; 1999a, b; 2001a, b, c, d; 2002; Abbasi *et al.*, 2010; 2013). Each accident is accompanied with great loss of property and often with loss of life and harm to the environment (Abbasi and Abbasi 2005; 2007 a, b, c; 2008; Tauseef *et al.*, 2010; 2011 a, b; Vasanth *et al.*, 2013). Ever so often one accident triggers another accident or a series of accidents, thereby escalating the disaster by 'domino effect' (Abdulhamidzadeh *et al.*, 2010; 2011).

The situation would have been much worse had the science of accident forecasting and loss prevention not been enhancing process safety since the 1970s (Khan and Abbasi 1998; Lees, 2005; Abbasi *et al.*, 2013; Rigas and Amyotte 2013). Prior to the 1970s, also, attempts had been made to assess risk of likely accidents and take steps to prevent them but two major disasters that occurred in the 1970s ─ the Flixborough tragedy of 1974 the Seveso accident of 1976 ─ made the scientific world enhance its attention towards accident prevention like never before.

A lot of old techniques were refined and advanced as also newer techniques were developed (Lees 2005; Abbasi *et al.*, 2013). The hazard and operability (HAZOP) study is one of them.

1.1 The Flixborough and the Seveso disasters

We present a recapitulation of the Flixborough and the Seveso disasters which both could have been easily avoided had a systematic HAZOP study been done for each plant and safety measures kept in place accordingly.

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The Flixborough disaster: The Flixborough disaster is perhaps the most discussed and dissected of all accidents in chemical process industry. What might have happened and how the accident could have been averted continues to be assessed and debated to this day.

The Flixborough Plant of Nypro Limited, UK, wasbuilt to produce caprolactum which is thebasic raw material for the production of Nylon, a globally popular synthetic thread of that era. The process required circulation of large quantities of cyclohexane through the reactors under elevated pressure (about 8.8 Kg/cm^2) and temperature (155°C). To start with, cyclohexanol is highly flammable, similar to petrol, and the reaction it was involved in at Nypro was exothermic. The hazard was increased manifold due to the above‒normal pressure and temperature involved. Any leak ofcyclohexane had disastrous portants.

The cyclohexane plant at Flixborough consisted of astream of six reactors in series in which cyclohexanewas oxidised to cyclohexanone and cyclohexanol by airinjection in the presence of a catalyst (Figure 1, A).

As recounted by Lees (1996, 2005), on the evening of 27 March 1974, it was discoveredthat reactor number 5 was leaking cyclohexane. Thefollowing morning an inspection revealed that the leakhad extended by some 6 ft. This was a serious state ofaffairs and a meeting was called to decide the course ofaction. A decision was taken to remove reactor 5 and toinstall a bypass assembly to connect reactor 4 directlyto reactor 6 so that the plant operation could continue.

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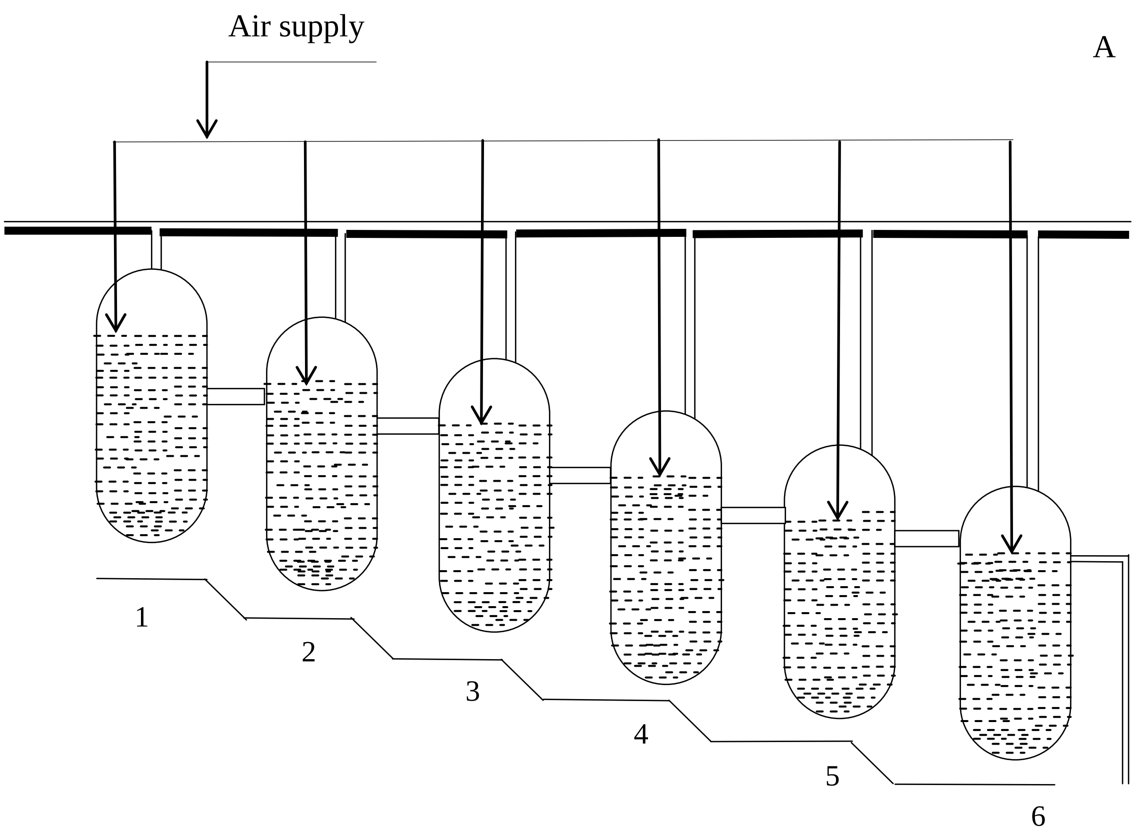
Scenes of the Flixborough disaster (alchetron.com/Flixborough-disaster)

The openings to be connected on these reactors were of28" diameter, but the largest pipe which was availableon site and which might be suitable for the by-pass was only of 20" diameter. The two flanges were at differentheights so that the connection had to take the form of adogleg of three lengths. Calculations were done tocheck that a) the pipe had large enough cross-sectionalarea for the required flow b) that it was capable ofwithstanding the pressure as a straight pipe.



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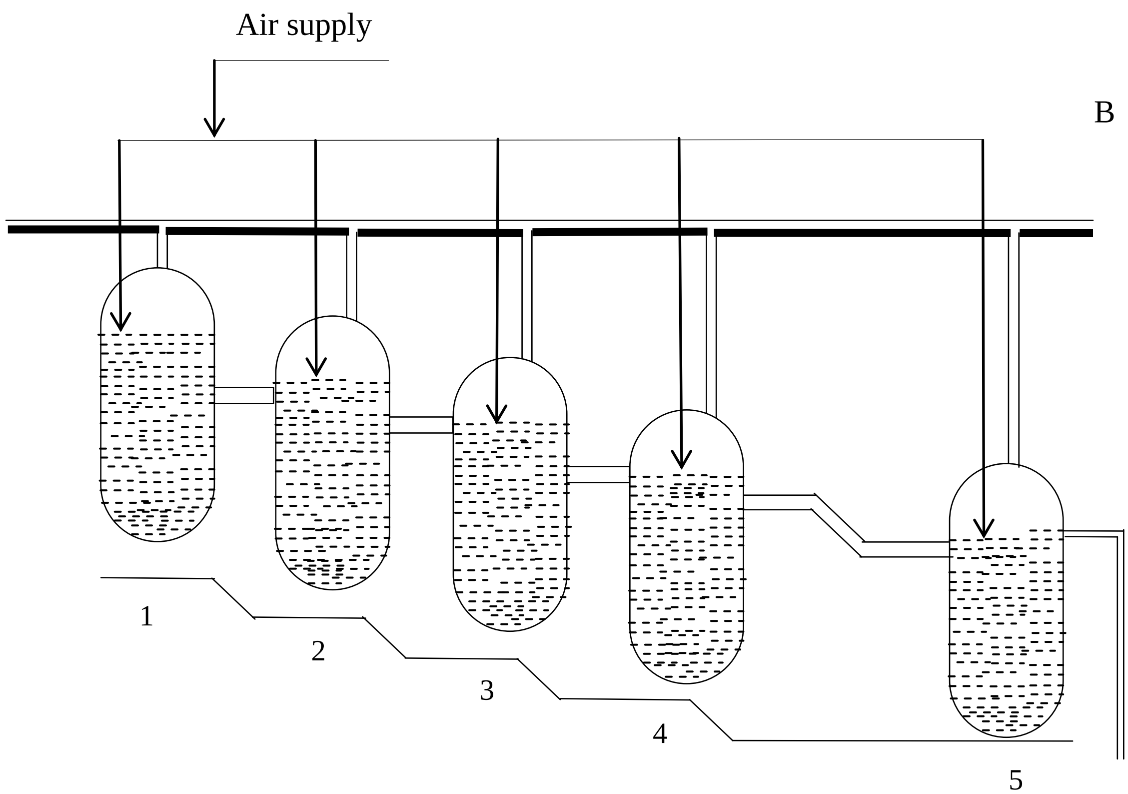

Figure 1: Simplified depiction of the chain of reactors that were involved in the Flixborough disaster. The figure at the top (A) shows the normal sequence of the six reactors. The figure at the bottom (B) shows the dog-leg shaped connection made between the fourth and the sixth reactor after reactor number 5 had been removed after it had developed a leak.

But no calculations were done which took into accountthe forces arising from the dog-leg shape of the pipe;no drawing of the by-pass pipe was made other than inchalk on the workshop floor; and no pressure testingwas carried out either on the pipe or on the completeassembly before it was fitted. A pressure test wasperformed on the plant, after the installation of thebypass, but the equipment was tested to a pressure of 9Kg/cm^2. Further, the test was pneumatic not hydraulic(Lees, 1996).

The plant was restarted. Initially the bypass assembly (Figure 1, B) gave no trouble. On May 29, 1974 the bottom valve onone of the vessels was found to be leaking. The plantwas again shut down for repairs, and restarted on June1. A sudden rise in pressure up-to 8.5 kg/cm^{2}occurred early in the morning when the temperature inReactor-1 was only 110°C and lesser in other reactors.Later that morning, the pressure reached 9.1-9.2 Kg/cm^2.

During the late afternoon there occurred a rupture in the dog-legshaped bypass system. It resulted in the escape of large quantities of cyclohexane which formed a vapour cloud. It soon caughta spark, and there was a massive vapourcloud explosion. The blast and the fire destroyed not only thecyclohexane plant but also several other plants in itsvicinity.

The blast instantly killed 28 personsworking in the factory and injured 36 others. Injuries and damage were widespread even outside the factory but, luckily, noone waskilled. Of the 28 people who died 18 were in thecontrol room. The main office of thefactory was demolished by the blast of the explosion.Mercifully the accident had occurred on a Saturdayafternoon when the offices were not occupied. If theyhad been, the death toll would have been much higher.

Property damage extended over a wide area, and apreliminary survey showed that 184 houses and 167shops and factories had suffered to a greater or a lesserdegree.

The Seveso disaster: On the morning of Saturday, 10July 1976, a safety valve of a reactor at theIcmesa Chemical Company at Seveso, a town of about17,000 inhabitants some 15 miles from Milan (Italy), vented 2 Kg of lethalTCDD - (2,3,7,8, - tetrachloro dibenzoparadioxin) into the air. It formed a white cloud which drifted over a part of the town. Heavyrainfall brought the cloud to earth thereby seriously contaminating a large area of the Seveso town. Nearby towns of Meda, Desio, Cesano, and Maderno were also effected.

In the immediate area of the release the vegetation was heavily contaminated and within days a total of 3,300 animals died in that area. On the 4th daya child fell ill and on the 5th day civil authoritiesdeclared a state of emergency in Seveso. An area ofsome 3 square Km was declared as contaminated andpeople were asked to avoid contact with the vegetationor eating anything from this area. Over 80,000 animals were slaughtered to prevent TCDD from entering the food chain. The contaminatedarea was later sought to be closed completely.On July27 the first evacuation of some 250 people took place.By the end of July, 250 cases of skin infection hadbeen diagnosed.

In early August it was found that thearea contaminated was about 5 times larger than wasoriginally thought (Lees, 1996).

Dead animals and an effected child at Seveso (alchetron.com/Seveso-disaster)

There have been accidents involving TCDD releaseprior to the Seveso disaster. At Ludwigshafen, fiftyfivepersons were exposed when there was accidentalTCDD release in 1953, and many developed severesymptoms of TCDD poisoning. Various measures weretaken to decontaminate the plant building, includingthe use of detergents, the burning off of the surfaces,the removal of insulating material and so on, but thesewere not effective and eventually the whole buildinghad to be destroyed. In another accident at Duphar in1963, a leak of 0.03-0.2 kg of TCDD occurred. Some50 persons were involved in cleaning up the leakage, of whom four subsequently died, and about a dozensuffered occasional skin troubles. The plant was sealedfor ten years and then dismantled from the inside brickby brick, the rubble was embedded in concrete, and theconcrete blocks were sunk in the Atlantic. Five yearslater yet another accident involving TCDD releaseoccurred at Bolsover. It involved a runaway reaction in a trichloro phenol reactor, similar to one thatlateroccurred at Seveso. The reaction reached 250°C, thereactor exploded and the supervising chemist waskilled. The plant was closed down, and then reopenedafter two weeks when it appeared that workers exposedhad suffered no ill effects. But within seven months, 79persons complained of TCDD symptoms. The plantwas dismantled and buried in a deep hole. But the storydid not end there; three years later contractors on thesite developed TCDD symptoms. The only apparentpossible source of contamination was a metal vesselwhich had been thoroughly cleaned and subjected tosensitive testing.

The lesson that emerged from Seveso was that pressurerelief valves on plants handling highly toxic substancesshould not discharge to atmosphere but to a closedsystem. But several hazardous units didn't bother toimplement the lesson learnt from Seveso. UCC was one such unit. Had its pressure relief valvesvented the deadly methyl iso-cyanategas into closed space instead of open air, the terrible Bhopal gas tragedy would not have occurred.

2. The birth of HAZOP

During the 1960s it had occurred to the celebrated process safety expert Traver Kletz, who was then Safety Advisor at the Imperial Chemical Industries (ICI), that if any equipment carries a probability of failure, it also carries a risk of failure. The idea crystallized to acquire the name HAZOP. In good time HAZOP was defined as *the application of a formal, systematic critical examination of the process and the engineering intentions of new or existing facilities to assess the potential for malfunctioning of individual pieces of equipment, and the consequential effects on the facility as a whole.*

In simpler terms HAZOP does a structured examination of each process unit, existing and due-to-be commissioned, to see what kind of deviations from the ideal operation can occur and what harm may be caused by such diviations.

3. Features of a typical HAZOP

The happenings of 1970s stimulated work towards development of HAZOP which took shape at the Imperial Chemical Industries (ICI), UK, by 1974 but has gone through several modifications as it has been put to practice (ICI, 1974; Kletz, 1985; Andow et al., 1980; Knowlton, 1982, 1989; McKelvey, 1988). As described by Abbasi *et al.*, (2013), the basic principle of a HAZOP study is that normal and standard conditions are safe, and hazards occur only when there is a deviation from normal conditions. HAZOP seeks to identify the deviations and grade the consequent hazards on the basis of extents of likely severity. In HAZOP study experts are expected to make intelligent guesses in the identification of hazard and operability problems. In a typical HAZOP study, design and operation documents (piping and instrument diagrams, process flow diagrams, material flow diagrams, and operating manuals) are examined systematically by a group of experts. These experts ought to represent all disciplines associated with the design, operation and maintenanceof the process plant being assessed. They are tasked to consider each and every likely deviation to identify all abnormal causes and adverse consequences for all possible deviations from normal operation that could arisefor each unit of the plant. To ensure that all possible malfunctions and deviations are covered, the HAZOP team members are guidedwith a set of guide words for generating the process variable deviations. A typical list of such guide words and their definitions is given in Table 1.

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Table 1: Typical HAZOP guide words and their physical significance (Abbasi *et al.*, 2013)

Guide word	Meaning	Parameter	Deviation
None	Negation intention	Flow	No flow
		Level	Zero level
Less	Quantitative decrease	Flow	Low flow rate
		Level	Low level
		Temperature	Low temperature
		Pressure	Low pressure
		Concentration	Low concentration
More	Quantitative increase	Flow	High flow rate
		Level	High level
		Temperature	High temperature
		Pressure	High pressure
		Concentration	High concentration
Reverse	Logical opposite	Flow	Reverse flow rate
		Pressure	Reverse pressure
Part of	Qualitative decrease	Concentration	Concentration decrease
		Flow	Flow decrease
		Level	Level decrease
As-Well-As	Qualitative increase	Concentration of impurity	Concentration increase
		Temperature of substance	Temperature increase
		Level of impurity	Level increase
		Pressure of substance	Pressure increase
		Flow of impurity	Flow increases
Other Than	Complete substitution	Concentration of desired substance	Concentration zero
		Level of desired substance	Level zero
		Flow of desired substance	Flow rate zero

The salient gains from a HAZOP study are:

- It gives an idea of priorities for detailed risk analysis;
- it provides first information of the potential hazards, their causes, and consequences;
- it indicates some ways to mitigate the hazards;
- it can be performed at the design stage as well as the operational stage;
- it provides a basis for subsequent steps in the total risk management program.

Tables 2 and 3 illustrate two of the typical HAZOP tables. A large number of such tables are generated in any HAZOP study which is reflective of the tedious nature of the HAZOP exercise.

Table 2: A typical HAZOP table for possible deviations in operating pressure in an esterifier unit (Abbasi *et al.*, 2013)

Deviation	Causes	Consequences	Remark
High pressure	Specific knowledge Vacuum pump not working properly; high pressure outlet from melter; out flow of methanol is low; outlet valve is choked; low temperature in esterifier; leak of vacuum from esterifier	Low product yield; poor quality of product; low methanol collection; adverse impact to poly condensation unit	Moderately hazardous
High pressure	General knowledge Leak in input line; leak in the reactor; outlet valve is not open; high inflow of reactant	Poor quality of product; high flow rate to next unit; chances of leak from the unit	Moderately hazardous
Low pressure	Specific knowledge Excess working of vacuum pump; high temperature thus fast reaction causing further vacuum; presence of impurity; low pressure input	High reaction rate causing further low vacuum; high outlet flow rate; chances of side reaction; hot spot formation; chances of esterifier damage due to excess vacuum	Hazardous
Low pressure	General knowledge Low feed flow rate; highout let flow rate; unwanted side reaction; vacuum indicator faulty	Product quality change; high outlet flow rate causing excess load to the next unit; chances of leak due over vacuum	Hazardous

Table 3: A typical HAZOP table for possible deviations in level of the chemical in melter unit (Abbasi *et al.*, 2013)

Deviation (guide word)	Causes	Consequences	Remark
Low level	Specific knowledge Low flow rate of MEG; low flow rate of PTA; no raw material available at storage; high temperature in melter	Probability of running dry; overheating leading to failure; high temperature at outlet; chances of leak and subsequent fire	Hazardous
Low level	General knowledge Leak in feed line; leak in melter; inlet valve choked; non-availability of raw materials	Low outlet flow; excess heating; chances of leak	Hazardous
High level	Specific knowledge High flow rate of MEG; high flow rate of PTA; pump running over-speed; outlet valve not open or choked; low temperature in melter	Over-pressurisation of vessel that may cause leak; not proper mixing; high outlet flow rate; adverse effect to esterification unit	Moderately hazardous
High level	General knowledge Outlet valve choked; level indicator faulty; presence of foreign material	Accumulation of material; over-pressurisation which may cause adverse affect to the unit operation; poor quality at outlet;	Moderately hazardous

4. Limitations of HAZOP

In its original, and thus far the most widely used form, HAZOP has four major limitations. The first arises from the assumptions underlying the method and is a limitation (perhaps intended) of scope. The method assumes that the design has been carried out totally in accordance with the appropriate codes and is 'perfect' — in other words safe as long as no deviations occur in its implementation. Accordingly it is presupposed that the design is appropriate for the requirements of normal operating conditions.But if it is not really so, HAZOP has no capability to identify the design flaw, less so to correct it. A conventional HAZOP only tries to identify deviations from the supposedly 'ideal' situations (Abbasi *et al.*, 2013; Pasman, 2015).

The second limitation is one which is neither intended, nor desirable, but is inherent in the method. For example HAZOP is not inherently well-suited to deal with spatial features associated with plant layout and their resultant effects (Khan and Abbasi, 1998a). The effect of any deviation occurring in a process unit will not be confined to that unit but will transmit downstream. But conventional HAZOP can not deal with it.

A third major limitation of HAZOP is that it needs large inputs of time and expert manpower. As the efficiency and accuracy of the study is fully dependent on the experience and sincerity of the expert team members, any limitations in manpower selection or performance can seriously harm the success of any HAZOP (Abbasi *et al.*, 2013). As brought out by Baybutt (2015 a, b), teams sitting on a HAZOP study may miss scenarios, neglect after-thoughts, become complacent, and suffer from fatigue due to the inherently tedious and repetitive nature of HAZOP. Even basic mistakes in considering the design intents, process parameters, guide words, initiating events and ways of operation are possible. There can be gaps in full technical coverage and documentation.

The fourth major limitation is the requirement of time and costs. It may take a team of atleast five experts anything from 1 week to 8 weeks ─ depending on the size of the plant ─ to carry out a HAZOP study. Given that a HAZOP is required once in 5 years, the cumulative costs are high.

Despite these limitations which have been reduced in degree to some extent by innovations described below, HAZOP remains the most favoured technique for hazard identification and assessment (Khan and Abbasi, 1998a; Pasman, 2015).

5. Innovations to overcome the limitations of HAZOP

The power of HAZOP on one hand, and its limitations on the other, have prompted a lot of efforts toenhance the utility of HAZOP and make it less burdensome and yet quicker (Khan and Abbasi, 1998a; Dunjo *et al.*, 2010; Pasman, 2015; Pasman and Rogers, 2016).

It can be said that HAZOP is midway between two other powerful PHA techniques—FTA and FMEA. HAZOP follows a deductive approach (downward) to pick initiating events (deviations), and then follows the inductive method (upward) asking what would happen to the system. This is the reason for the success of HAZOP and underscores its widespread usage compared to other well-known analysis systems.

HAZOP is also credited as having inspired the improvement in other process safety methodologies, especially layer of protection analysis (LOPA).

5.1 The thrusts: developing hybrids of HAZOP and other techniques to get 'the best of several worlds': Integrating HAZOP with FMEA, FTA etc

Whereas the hazard-identification stage in HAZOP is based upon using established guidewords and parameters for generating deviations of the design intent, failure made and effects analysis (FMEA) considers the failure modes of specific equipment. This close relationship between HAZOP and FMEA have generated much research on combining the two to increase the efficiency and the quality of both.

Attempts to extend the HAZOP's role from identifying hazards to evaluating their impacts, have also led to the integration of HAZOP with fault tree analysis (FTA). It has been felt that a thorough HAZOP, linked carefully with the FTA, minimized the contributions of uncertainty from three areas:

1. Which initiating events must be considered;
2. what is the frequency of occurrence of these initiating events and;
3. which criterion should be applied in consequence modeling and estimation.

Other hybrids include combining indice-based screening with HAZOP to speed-up the preliminary hazard analysis (PHA). HAZOP provides inputs for maximum credible accident analysis and other steps in risk assessment.

5.2 The thrusts: Stream-based nodes rather than equipment-based nodes.

In a stream-based node, a stream is followed from its inception to its logical conclusion. This is especially useful when considering flow deviations, because a flow disruption in any part of the stream affects all parts or at least all downstream parts of the stream. As stream-based nodes are much larger than typical equipment-based nodes, they overcome the tendency of HAZOPs to create tunnel vision.

Operating procedures can be introduced during the stream-based node discussion providing an opportunity to do a process HAZOP and a procedure HAZOP simultaneously. The latter can at times provide more insight than the former. Conventional HAZOPs typically consider 'flow', 'pressure', 'temperature' and 'level' deviations even as most such deviations are caused by flow deviations.

5.3 The thrusts: making HAZOP more 'human'

An enduring criticism of the conventional HAZOP has been that it puts all the emphasis on equipment and process variables as likely accident triggers, discounting the human element or the cognitive aspect of the process operation. But the wisdom of hindsight that we have acquired from past accident analysis (PAA) tells us that the human element can be a major cause in starting or preventing, aggravating or mitigating, prorogating or containing an accident. Hence a lot of attention has been paid towards developing methodologies which consider human-machine interfaces, organizational style, management attitudes, and procedures and training.

As batch processes entail major human involvement, they have to be paid special attention.

5.4 The thrusts: cutting short the time and the drudgery ─ the work of Khan and Abbasi as noted by Dujo et al., 2010

Perhaps the most earnest work in the HAZOP field has been in making it quicker and less tiresome. These authors have been among the early explorers. To quote from a paper of Dunjo *et a*l., (20102), who mention the work of Freeman et al., (1992) in HAZOP time estimation and then state: "Five years later, Khan and Abbasi (1997d) improved this model, adding new factors and variables. The proposed model takes into account four different parameters (preparation time, meeting time, delay and report writing); and uses multivariable empirical equations. Additionally, the preparation and study time are function of three parameters: number of P&IDs, complexity of P&IDs and the skills of the team leader".

"Khan and Abbasi also published much work on automating HAZOP. Their first paper (Khan and Abbasi, 1997 b) analyzed the conventional HAZOP, identifying several factors affecting its effectiveness and reliability; they concluded that its conventional structure must be modified to ensure fast, efficient, and reliable results".

"They described their approach for optimizing HAZOP studies (OptHAZOP) that rests upon expert system knowledge. This base comprised a large collection of facts, rules, and information on various components of process plants, such as process deviations, their causes, and their immediate consequences for various components".

"To improve their first version, they generated a new knowledge-based software tool, termed TOPHAZOP (Khan and Abbasi 1997c) to speed up the OptHAZOP (1997). It identified general and specific causes and consequences of all probable process-deviations. The whole expert system (the so-called EXPERTOP) consisted of the following main modules: Knowledge base, inference engine, and user interface (Khan and Abbasi, 2000). Further work to improve specific features of this system and other applications are reported in Khan and Abbasi (1998a, 2001a,b; 2005)".

"Finally, Khan proposed a knowledge-based expert system for automating HAZOPs for offshore process facilities. The framework was aimed to enable HAZOPs at significantly lesser costs and with better accuracy than conventional HAZOPs".

6. What lies ahead

As brought out eloquently by Pasman and Rogers (2016) in a highly perceptive review, HAZOP is going strong, with inputs from information technology and artificial intelligence continuing to enhance its power while simultaneously making it quicker. More significantly, HAZOP is being made more versatile as well as 'paying' by extending the use of HAZOP reports beyond operability−related hazard assessment to audit, design, operator training and other domains. Possibility of using HAZOP study results to alert personnel in real time towards a developing upset and fault diagnosis is being explored.

Early attempts at extricating HAZOP from being 'local' (unit-focused) to 'global' (dealing with the whole plant as a system) made use of directed graphs, also called 'digraphs' (directed edges and nodes),representing flow and operational variables (Pasman, 2015). A digraph coded with guided workplace layers enabled generation of a three-dimensional influence structure. This enhanced flexibility and versatility. The next innovation of stream-based nodes, explained in Section 5.2,was the use ofcoloured Petri nets, mainly by Venkatasubramanian and co-workers

(Venkatasubramanian, 2011) to represent logistics. In it, the node colour isassociated with a specific property/value (Zhao *et al.*,2005).This was followed by the development of the Multi-level Flow Model (MFM) approach, which was originally formulated for simulation of nuclear power plant installations. MFM shows equipment objectives(source, transport, storage) and functions (sink, barrier, balance). It describes the interactions of mass, energy, and information flows, combined to flow structures (Wu, 2014). The D-higraph model which is more intuitive and insightful than MFM came next (Rodriguez and dela Mata, 2012). Besides possessing the MFM features, D-higraph is also able to show the plant's controls.

Acknowledgement

SAA thanks the Council of Scientific and Industrial Research (CSIR), New Delhi, for the Emeritus Scientist grant (21(1034)/16/EMR-II).

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