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Tomás Mac Sheoin. Justice for Bhopal! And No More Bhopals! *Three decades of national and international campaigning*. Pages 3-12.

Dissatisfaction with the responses of the responsible corporation, Union Carbide, and the Indian government to Bhopal resulted in a campaign by national and international NGOs (non-governmental organisations) over the past three decades. While initially the Indian and international campaigns were separate, over time greater international cooperation took place. In the immediate aftermath of the disaster local NGOs prioritised health, justice and rehabilitation issues, while international NGOs used Bhopal to question chemical industry process and environmental safety in their own countries, as well as internationally. Indian NGOs called on international NGO resources to gain legitimacy for their campaign, to use NGOs as proxies and to extend the geographical scope of the campaign, while international NGOs used Bhopal as an example to advance NGOs analyses and policies. Over the period of the campaign, Indian NGOs became more sophisticated in their campaigning. The international campaign has increasingly become an online campaign, involved in an image or reputational war with Dow Chemical, which took over Union Carbide, while the original campaign issues of justice and reparations over the process safety disaster were joined by similar issues related to environmental safety of abandoned toxic waste.

- **Keywords:** Bhopal; Catastrophe; NGO; Corporate campaign; Union Carbide; Dow Chemical

Mohsen Naderpour, Salman Nazir, Jie Lu. *The role of situation awareness in accidents of large-scale technological systems*. Pages 13-24.

In the last two decades, several serious accidents at large-scale technological systems that have had grave consequences, such as that at Bhopal, have primarily been attributed to human error. However, further investigations have revealed that humans are not the primary cause of these accidents, but have inherited the problems and difficulties of working with complex systems created by engineers. The operators have to comprehend malfunctions in real time, respond quickly, and make rapid decisions to return operational units to normal conditions, but under these circumstances, the mental workload of operators rises sharply, and a mental workload that is too high increases the rate of error. Therefore, cognivitive human features such as situation awareness (SA)—one of the most important prerequisite for decision-making—should be considered and analyzed appropriately. This paper applys the SA Error Taxonomy methodology to analyze the role of SA in three different accidents: (1) A runaway chemical reaction at

Institute, West Virginia killing two employees, injuring eight people, and requiring the evacuation of more than 40,000 residents adjacent to the facility, (2) The ignition of a vapor cloud at Bellwood, Illinois that killed one person, injured two employees, and caused significant business interruption, and (3) An explosion at Ontario, California injuring four workers and caused extensive damage to the facility. In addition, the paper presents certain requirements for cognitive operator support system development and operator training under abnormal situations to promote operators' SA in the process industry.

- **Keywords:** Situation awareness; Error taxonomy; Process safety; Abnormal situations; Operator support systems; Operators' training

Jinqiu Hu, Laibin Zhang, Zhansheng Cai, Yu Wang, Anqi Wang. *Fault propagation behavior study and root cause reasoning with dynamic Bayesian network based Framework*. Pages 25-36.

The Bhopal disaster was a gas leak incident in India, considered the world's worst industrial disaster happened around process facilities. Nowadays the process facilities in petrochemical industries have becoming increasingly large and automatic. There are many risk factors with complex relationships among them. Unfortunately, some operators have poor access to abnormal situation management experience due to the lack of knowledge. However these interdependencies are seldom accounted for in current risk and safety analyses, which also belonged to the main factor causing Bhopal tragedy. Fault propagation behavior of process system is studied in this paper, and a dynamic Bayesian network based framework for root cause reasoning is proposed to deal with abnormal situation. It will help operators to fully understand the relationships among all the risk factors, identify the causes that lead to the abnormal situations, and consider all available safety measures to cope with the situation. Examples from a case study for process facilities are included to illustrate the effectiveness of the proposed approach. It also provides a method to help us do things better in the future and to make sure that another such terrible accident never happens again.

- **Keywords:** Process safety; Root cause reasoning; HAZOP; Dynamic Bayesian network

E. Palazzi, F. Currò, B. Fabiano. *A critical approach to safety equipment and emergency time evaluation based on actual information from the Bhopal gas tragedy*. Pages 37-48.

As amply reported, after Bhopal disaster process safety got a boost worldwide and risk analysis got applied more generally. Even if the concept of inherent safety, strongly promoted by Trevor Kletz, represents one of the main lessons from this tragedy, in the first part of the paper we focus on Bhopal mitigation measures representing the ultimate relevant layer of protection. Starting from a technical analysis of the whole safety equipment of the plant and relevant empirical evidences, we face the short-cut design of critical safety devices suitable to mitigate release effects. The applied method allows a preliminary design and management tool to evaluate the effectiveness of safety systems and the impact on surroundings. In the second part, we develop an empirical-based framework allowing to identify emergency actions and intervention time and demonstrate how the implementation of these safety measures when reaching a critical pressure of 10 psig in Tank 610, even under the condition of protective equipment out of commission, would have surely mitigated such a high profile tragedy. The paper illustrates the determining contribution to this tragedy of such deficiencies in the safety procedures for handling abnormal situations and emergencies by the company.

- **Keywords:** Bhopal incident; Emergency planning; Human factor; Runaway reaction; Safety equipment design

Kamarizan Kidam, Haslinda A. Sahak, Mimi H. Hassim, Haslenda Hashim, Markku Hurme. *Method for identifying errors in chemical process development and design base on accidents knowledge*. Pages 49-60.

It has been claimed that the high accident rate in the chemical process industry is due to poor dissemination of accident knowledge that affects directly the level of learning from accidents. In response to this situation, this paper utilized past accident knowledge as a basis to develop a safety oriented design tool whereby the accident information were directly disseminated into plant design. The method was developed based on our previous accident analysis of design error in which the common design errors were ranked in accordance to their frequency and its origins during normal plant design project. Based on the design error ranking and its origin at a specific design phases, a method for design error detection is proposed. The method is expected to be able to identify the possible design error and its causes throughout chemical process development and design. The main objective is to trigger safe design thinking at the specific design phases so that appropriate action for risk reduction could be timely implemented. The Bhopal and BP Texas tragedies are used as case studies to test and verify the method. The proposed method can detect up to 74% of design errors.

- **Keywords:** Accident; Learning from accident; Design error; Error detection; Process lifecycle; Plant design

Russell A. Ogle, Sean J. Dee, Brenton L. Cox. *Resolving inherently safer design conflicts with decision analysis and multi-attribute utility theory*. Pages 61-69.

The 1984 Bhopal tragedy involved the toxic and reactive chemical methyl isocyanate (MIC). The enormous human toll of this tragedy spurred the development of the concept of inherently safer design (ISD), and several published studies have since demonstrated the application of ISD concepts to the Bhopal process. In 2008, the U.S. Chemical Safety Board (CSB) investigated a fatal explosion at a chemical plant in West Virginia, for which a potential (unrealized) outcome was the loss-of-containment of the large inventory of MIC stored onsite. The CSB asked the National Academy of Sciences (NAS) to investigate the application of ISD concepts to the design of the West Virginia plant. The NAS study indicated that one of the primary difficulties in evaluating and choosing between ISD alternatives was the need to satisfy conflicting design objectives. The NAS panel suggested Multi-attribute utility theory (MAUT) as a basis for evaluating ISD alternatives, but they did not illustrate its use in this report. Here, we illustrate the use of MAUT as a decision analysis tool for evaluating ISD alternatives, and show that the MAUT technique is an effective tool for resolving ISD conflicts. We demonstrate how to use MAUT to evaluate ISD alternatives by formulating utility functions and weights for the decision objectives. We also examine how the final ranking of alternatives varies with the weights.

- **Keywords:** Inherently safer design; Risk management; Decision analysis; Multi-attribute utility theory; Methyl isocyanate; Bhopal

Ming Yang, Faisal Khan, Paul Amyotte. *Operational risk assessment : a case of the Bhopal disaster*. Pages 70-79.

Accidental releases of hazardous chemicals from process facilities can cause catastrophic consequences. The Bhopal disaster resulting from a combination of inherently unsafe designs and poorly managed operations is a well-known case. Effective risk modeling approaches that provide early warnings are helpful to prevent and control such rare but catastrophic events. Probability estimation of these events is a constant challenge due to the scarcity of directly relevant data. Therefore, precursor-based methods that adopt the Bayesian theorem to update prior judgments on event probabilities using empirical data

have been proposed. The updated probabilities are then integrated with consequences of varying severity to produce the risk profile. This paper proposes an operational risk assessment framework, in which a precursor-based Bayesian network approach is used for probability estimation, and loss functions are applied for consequence assessment. The estimated risk profile can be updated continuously given real-time operational data. As process facilities operate, this method integrates a failure-updating mechanism with potential consequences to generate a real-time operational risk profile. The real time risk profile is valuable in activating accident prevention and control strategies. The approach is applied to the Bhopal accident to demonstrate its applicability and effectiveness.

- **Keywords:** Bhopal disaster; Operational risk assessment; Bayesian networks; Loss functions; Dynamic risk assessment; Accident precursor

Ashraf Labib. *Learning (and unlearning) from failures : 30 years on from Bhopal to Fukushima an analysis through reliability engineering techniques*. Pages 80-90.

Reliability engineering techniques such as failure mode effect analysis (FMEA), fault tree analysis (FTA), and reliability block diagrams (RBD) have been used to analyse the case of the Bhopal disaster (Labib and Champaneri, 2012), and subsequently used in the analysis of other disasters (Labib, 2014b), where it has been shown how such techniques can help in building a mental model of describing the causal effects of the disaster. The same case study of Bhopal was also investigated (Ishizaka and Labib, 2014) and a new logic gate in the fault tree method was proposed for analysing disasters and the benefits of using hybrid techniques of multiple criteria and fault analysis to evaluate and prevent disasters were demonstrated. In this paper an analysis of learning, and un-learning, from failures is carried out using a comparison between Bhopal and Fukushima, although they occurred in different industries, by comparing them we observe many similarities. This is followed by a compilation of different models based on FTA and RBD analysis of the Bhopal disaster which were an outcome of a series of workshops that were carried out to investigate the Bhopal disaster. This approach shows how the same case study can be viewed from different perspectives although the same modelling techniques were used. The paper then explores few interesting research questions such as how to evaluate different models? Do multiple models lead to better understanding of the case study? And are there any practical guidance to follow when studying root cause analysis?

- **Keywords:** Learning from failures; Unlearning; Bhopal; Fukushima; Fault tree analysis; Reliability block diagram

Rex T.L. Ng, Mimi H. Hassim. *Strategies for assessing and reducing inherent occupational health hazard and risk based on process information*. Pages 91-101.

Over the last few decades, the concept of inherent occupational health has gained increasing attention to reduce occupational hazards that may adversely impact workers' health. In order to assess occupational hazards in the chemical process, different inherent occupational health assessment methods have been developed at the early stages of process development and design. The methods in the order of process information availability – ranging from the detailed piping and instrumentation diagrams to a simple sketch of process concepts are the: occupational health index (OHI), health quotient index (HQI) and inherent occupational health index (IOHI). This paper proposes systematic heuristic frameworks to assist process designers and engineers in assessing and reducing inherent occupational health hazards or risks based on process information availability. Strategies for reducing health hazards or risks in the OHI, HQI and IOHI methods based on inherently safer design (ISD) keywords of minimization, substitution, moderation and simplification are included in this study. It is worth mentioning that the proposed frameworks act as guidelines for design engineers in systematically selecting

the appropriate index and methodology to assess and reduce health hazards/risks based on the availability of the process information. A case study is solved to illustrate the proposed framework.

- **Keywords:** Inherent occupational health; Process design; Process improvement; Inherently safer design; Emission reduction

Yang Miang Goh, Sherry Tan, Kean Chung Lai. *Learning from the Bhopal disaster to improve process safety management in Singapore*. Pages 102-108.

The Singapore process industry is mainly made up of chemical and energy companies such as Mitsui Chemicals, Clariant, Exxon Mobil, Shell, Sumitomo, Petrochemical Corporation of Singapore and Infineum. Majority of these companies are located on Jurong Island, southwest of Singapore. Jurong Island houses nearly 100 leading petroleum, petrochemicals and specialty chemicals companies and the total investment is about S$42 billion in total. With a land surface area of only 716 km2 and a high concentration of process plants, the Singapore government places strong emphasis on safety and risk management. In this paper, four process industry veterans from the government, academic and private sectors were interviewed. Through the interviews, the authors sought to understand the veterans' perspectives on lessons that the Singapore process industry should learn from the Bhopal disaster. The veterans expanded their thoughts beyond the Bhopal disaster and provided many insights and suggestions critical to process safety management in Singapore and other countries. A systemic model of process safety management was derived from the interviews and key elements of operational process safety management were identified. In addition, a research agenda was identified based on the inputs from the veterans.

- **Keywords:** Process safety; Bhopal disaster; Lessons learnt; Singapore; Expert interviews; Qualitative study

Rim Saada, Dipesh Patel, Basudeb Saha. *Causes and consequences of thermal runaway incidents : will they ever be avoided?* Pages 109-115.

A study of runaway incidents involving thermal chemical reactions in the UK over the past 25 years (1988–2013) has been carried out. The objective of this study is to determine possible causes of thermal runaway incidents. A statistical analysis of the underlying problems that led to thermal runaway incidents has been provided. A comparison of the current study on thermal runaway incidents with those identified prior to 1988 has been carried out. This study clearly shows that lessons have not been learnt from thermal runaway incidents caused by operator errors, management failures and lack of organised operating procedures. These factors have been the possible causes of about 77% of all the thermal runaway incidents analysed in this study. The number of fatalities and injuries as a result of thermal runaway incidents has increased by ~325% and ~279%, respectively, in the last 25 years even though the number of incidents was significantly less. On the basis of this analysis, several recommendations have been proposed that could help to minimise the risks associated with any thermal runaway incidents in the future.

- **Keywords:** Inherent safety; Hazard identification; Health and environment; Process design; Risk assessment; Thermal runaway reactions

Hung-Cheng Chou, Chi-Tang Yeh, Chi-Min Shu. *Fire accident investigation of an explosion caused by static electricity in a propylene plant*. Pages 116-121.

This study investigated a 2010 fire and explosion that occurred at a polypropylene (PP) and copper-clad laminate high-tech plant in Taiwan. Liquid acetone leakage caused the fire and explosion. One person was killed and five were injured; property damage was estimated at US$20 million. In contrast to conventional plants, high-tech plants have sophisticated instrumentation, highly complex pipelines, and confined spaces. In addition, the floor area in a high-tech plant is large and frequently contains a channel through the ground floor to the second or third floor. This channel design enables the fire compartment to be destroyed. Therefore, the system cannot confine the fire to a specific area, thus hindering fire-relief operations. In this study, the original fire outbreak occurred in the PP processing area on the ground floor. The acetone storage tank was located on the third floor. The investigation conducted at the fire site of the situations of the burning (bursting) loss determined that the acetone liquid leaked and dripped from floor cracks and tunnel oven to the PP processing area. Because the PP manufacturing process rapidly generates static electricity, the flammable liquids made contact with the source of ignition, which caused the explosion and fire. Various procedures, such as those involving the operating environment of production, packaging, and processing in a high-tech plant, are likely to produce static electricity in a workplace. Improved electrostatic management can prevent the loss of property and lives, liquid acetone leakage, and loss of equipment caused by static electricity fire.

- **Keywords:** Fire and explosion; Liquid acetone leakage; Acetone storage tank; Burning (bursting) loss; Static electricity; Flammable liquids