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Adam S. Markowski, Agata Kotynia. *"Bow-tie" model in layer of protection analysis*. Pages 205-213.

Layer of protection analysis (LOPA) is a semi-quantitative method that assesses the risk of an accident scenario in the process industry. The calculation is similar to an event tree principles applied to a single worst case scenario. However, process risk assessment requires to include all spectrum of possible accidents that subsequently may exceed the company risk tolerance level. In order to obtain more appropriate and accurate analysis the complete accident scenario model need to be used. This is the best provided by a "bow-tie" approach being a composition of fault and event tree. The quantitative application of the "bow-tie" model is proposed in the methodology of LOPA. Such an approach increases benefits in the risk management process. Further part of this paper focuses on the application of fuzzy logic system (FLS). It enables to cope with the lack of knowledge of reliability data that describe probabilities of initiating events (causes) and safety functions. The "bow-tie" model as well as the application of fuzzy logic may affect the simplicity of traditional LOPA. However, it can be solved by appropriate computer-aided analyses. The case study of a typical hexane distillation unit illustrates the application of the proposed method. **Highlights:** ► The quantitative application of the "bow-tie" model in the methodology of LOPA is proposed. ► Subjective and vague problems connected with frequency data are solved with help of FL. ► This concept allows for precise determination of safety measures for specific accident scenario. ► The practical example illustrates presented approach.

- **Keywords:** Fuzzy logic; Fault and event tree analysis; "Bow-tie" accident scenario model; Layer of protection analysis; Risk analysis; Process risk assessment

Jordi Dunjó, Vasilis M. Fthenakis, R.M. Darbra, Juan A. Vílchez, Josep Arnaldos. *Conducting HAZOPs in continuous chemical processes : Part I. : criteria, tools and guidelines for selecting nodes*. Pages 214-223.

The aim of the present paper is to provide new tools and criteria for conducting HAZOPs in continuous chemical processes (e.g., petroleum-refining processes). These are mainly based on five HAZOPs of different systems, conducted by different teams. Its scope covers the organizational step of the HAZOP study, which principally entails selecting the nodes to be analyzed and estimating the time required to examine them. These two aspects are focused on defining and planning the sessions that will be necessary to complete a HAZOP study. Part I of this paper focuses on developing tools, guidelines, and

criteria for selecting and sizing nodes. A methodology for selecting nodes is illustrated and mathematical models for predicting the number of nodes to be selected and the time needed to select each node are presented. Part II focuses on developing a HAZOP time estimation model for predicting the time required to perform the whole HAZOP, from its preparation and organization up to the release of the first HAZOP draft report. **Highlights:** ► The present paper provides tools and criteria for conducting HAZard & Operability studies (HAZOPs) in complex continuous chemical processes. ► We offer guidance on how to select nodes, and which node size is the optimum one for HAZOP brainstorming. ► We propose a Node Selection Methodology (NSM). ► A simple model was developed for predicting the number of nodes to be selected according to the process size and complexity.

- **Keywords:** HAZOP; Nodes Selection Methodology; Nodes Selection Modeling; Process Hazard Analysis

Jordi Dunjó, Vasilis M. Fthenakis, R.M. Darbra, Juan A. Vílchez, Josep Arnaldos. *Conducting HAZOPs in continuous chemical processes : Part II. : a new model for estimating HAZOP time and a standardized approach for examining nodes*. Pages 224-233.

The HAZOP organization phase entails two main tasks to ensure the success of the study, especially when reviewing complex continuous chemical processes (e.g., petroleum-refining processes). The first task deals with selecting the nodes, as we discussed in Part I of this paper. It addresses that task by proposing and justifying tools for and criteria on how to break a process into manageable sections that could be reviewed independently (i.e., nodes selection). Part II describes the development of a time-estimation model for planning HAZOP sessions. Its practical value was confirmed with field work and data analyses of five HAZOPs. Furthermore, we focus on optimizing the time spent in examining selected nodes. This papers also introduces a Deviations Structural Hierarchy (DSH) for treating deviations. Finally, considering the Nodes Selection Methodology (NSM) defined in paper I, the HAZOP time-estimation model (HTEM), and the Deviations Structural Hierarchy (DSH), we present the key tools, criteria, and guidelines for leading HAZOPs for highly complex processes. **Highlights:** ► A time-estimation model for planning HAZOP sessions is presented in this paper. ► The paper also introduces a Deviations Structural Hierarchy (DHS) for treating deviations. ► Keytools, criteria and guidelines for leading HAZOPS in complex continuous chemical processes are presented. ► The new procedure presented in this paper, reinforces the HAZOP structure and ensures reviewing the key factors that could entail hazardous scenarios.

- **Keywords:** Process hazard analysis; HAZOP; HAZOP time-estimation model; Deviations Structural Hierarchy; Nodes Selection Methodology

B.J. Lowesmith, G. Hankinson, D.M. Johnson. *Vapour cloud explosions in a long congested region involving methane/hydrogen mixtures*. Pages 234-247.

A series of large scale vapour cloud explosions in a long congested region were conducted using methane/hydrogen mixtures. The congested region measured 3 m × 3 m × 18 m long and was preceded by a confined region which allowed an explosion flame with some initial flame speed and turbulence to be generated which then entered the congested region. During the experiments the flame speed and explosion overpressure were measured through the congested region. The hydrogen content in the methane/hydrogen mixture was varied from 0 to 50% by volume. A key objective was to determine factors that could lead to continued flame acceleration through the congested region, such as the hydrogen concentration, the initial flame speed entering the congestion and the level of congestion. The results are reported together with some

detailed observations of the complex nature of pressure traces produced by explosion events of this type. **Highlights:** ► Vapour cloud explosion experiments in long congested regions are reported. ► The fuel gases were methane/hydrogen mixtures with up to 50% by volume hydrogen. ► The main objective was to assess the risk of high overpressures or even DDT. ► With over 40% H2 in the fuel there is an increased risk of damaging overpressures.

- **Keywords:** Vapour cloud explosions; Methane/hydrogen mixtures; VCE; Large scale experimental data

Uday Kumar Chakrabarti, Jigisha K. Parikh. *Route risk evaluation on class-2 hazmat transportation*. Pages 248-260.

Incidents involving hazardous material (hazmat) road tankers carrying class-2 materials may pose the greatest danger to the people and property along the transport route because of their storage condition on the transport vessel i.e. stored either in pressurized vessels or in cryogenic containers and lead to severe consequences in terms of fatalities, injuries, evacuation, property damage and environmental degradation. The worst case of release may result into phenomenon like Boiling Liquid Expanding Vapor Explosion (BLEVE) due to collision related catastrophic failure of vessel and an Unconfined Vapor Cloud Explosion (UVCE) due to delayed ignition following a large release. The impact zones or vulnerable areas have been identified along two designated. State highway routes passing through an important industrial corridor in Western India and mapped on a GIS enabled local map. HAMS-GPS software was used for the analysis of flammables and ALOHA for toxic hazmat consequences. The route risks are compared which have been estimated based on the population likely to be affected within the lethality impact areas created by the worst case release scenarios of different class-2 hazmats, namely LPG, ethylene oxide, propylene, 1,3-Butadiene, ammonia and chlorine, enabling proper routing decision by local authorities and also for planning emergency mitigating actions. **Highlights:** ► The ongoing research aims at route risk evaluation from class-2 hazmat transportation. ► Class-2 hazmats due to their storage conditions, pose BLEVE and UVCE hazards. ► These worst-case scenarios cause fatality and injuries along the transport routes. ► Consequence analysis was conducted for these hazmats to identify the impact areas. ► Route risks estimated based on population exposure within the impact area, compared.

- **Keywords:** Hazmat; Risk; Loss of containment; BLEVE; Population density; Consequence assessment

S. Perez-Vega, Senior Peter, I. Salmeron-Ochoa, A. Nieva-de la Hidalga, P.N. Sharratt. *Analytical hierarchy processes (AHP) for the selection of solvents in early stages of pharmaceutical process development*. Pages 261-267.

The AHP (analytical hierarchy process) mathematical model was implemented into a tool aimed to aid the selection of solvents in the early stages of pharmaceutical process development. The tool assesses environmental implications using the information available in the early stages of development. Solvent properties, characteristics, and their relationship with common operations are exploited. In order to make the approach user-friendly, the tool was incorporated into a VB.NET application. The user obtains a ranked list of potentially good solvents. The result can be used as a starting point in solvent selection. The chemist can explore implications of the solvent selected not only from synthesis perspective, but also from an HSE perspective. A case study is presented for the replacement of benzene, where through a series of steps the chemist inputs ideal solvent characteristics and the importance of each characteristic in the decision. In this case solvent replacement is based in finding a solvent with the same solubility behaviour, but with less toxicity problems and at low cost. The tool considers a wide pool of solvents

in a short time and produces ranked choices according to the chemist needs; taking account of both synthesis and HSE perspectives. **Highlights:** ► The AHP mathematical model was implemented into a tool aimed to aid the selection of solvents in the early stages of pharmaceutical process development. ► The tool assesses environmental implications using the information available in the early stages of development. ► The user obtains a ranked list of potentially good solvents. ► The chemist can explore implications of the solvent selected not only from synthesis perspective, but also from an HSE perspective.

- **Keywords:** Solvents; AHP; Decision; Early process development; HSE

Hi-Soo An, Seoung-Soo Park, Ki-Hyoung Kim, Seok-Un Park, Tae-In Ohm. *Treatment of PCB-contaminated pole transformers by vacuum thermal recycling with voltage adjuster*. Pages 268-274.

In this study, we employed vacuum thermal recycling (VTR) with a voltage adjuster, herein referred to as the 'improved VTR method', to treat polychlorinated biphenyl (PCB)-contaminated pole transformers. We evaluated the performance of the improved VTR method for PCB removal using 50- and 75-kVA pole transformers containing 11.8 and 214.8 mg/L of PCBs, respectively. The total residual PCBs were below the detection limit for all samples: copper coil, iron core, insulating paper, wood, and porcelain. To increase the temperature of the copper coil from room temperature to 200–230 °C, 292–406 kWh of power was consumed for the conventional VTR method whereas 102–131 kWh was consumed for the improved VTR method. Further, the time required to heat the transformers under the same condition was 131 and 292 min for the improved and the conventional VTR method, respectively. The temperature increase was achieved by the

improved VTR method at input energies of only ~5 kWh for the 75-kVA transformer and

3 kWh for the 50-kVA transformer. These results suggest that the improved VTR method is more cost-effective than the conventional VTR method because of its low power consumption and treatment time. **Highlights:** ► We investigated the efficiency of the improved VTR method for treating pole transformers. ► Conventional VTR required a power of 292–406 kWh, but improved VTR 102–131 kWh. ► The voltage adjuster adapted for improved VTR with input of 5 kWh for 75 kVA transformer. ► The improved VTR was more cost effective than conventional VTR for treating transformers.

- **Keywords:** PCBs; Voltage adjuster; Vacuum thermal recycling; Pole transformer