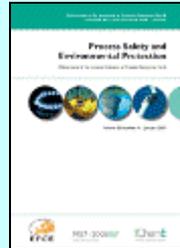


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Refaul Ferdous, Faisal Khan, Rehan Sadiq, Paul Amyotte, Brian Veitch. *Analyzing system safety and risks under uncertainty using a bow-tie diagram: An innovative approach.* Pages 1–18.

A bow-tie diagram combines a fault tree and an event tree to represent the risk control parameters on a common platform for mitigating an accident. Quantitative analysis of a bow-tie is still a major challenge since it follows the traditional assumptions of fault and event tree analyses. The assumptions consider the crisp probabilities and “independent” relationships for the input events. The crisp probabilities for the input events are often missing or hard to come by, which introduces *data uncertainty*. The assumption of “independence” introduces *model uncertainty*. Elicitation of expert's knowledge for the missing data may provide an alternative; however, such knowledge incorporates uncertainties and may undermine the credibility of risk analysis.

This paper attempts to accommodate the expert's knowledge to overcome missing data and incorporate fuzzy set and evidence theory to assess the *uncertainties*. Further, dependency coefficient-based fuzzy and evidence theory approaches have been developed to address the *model uncertainty* for bow-tie analysis. In addition, a method of sensitivity analysis is proposed to predict the most contributing input events in the bow-tie analysis. To demonstrate the utility of the approaches in industrial application, a bow-tie diagram of the BP Texas City accident is developed and analyzed.

- **Keywords:** Uncertainty; Bow-tie analysis; Expert knowledge; Interdependence; Likelihood; Sensitivity analysis

Naser Badri, Farshad Nourai, Davood Rashtchian. *A multivariable approach for estimation of vapor cloud explosion frequencies for independent congested spaces to be used in occupied building risk assessment.* Pages 19–30.

API Recommended Practice 752 is one of the most referenced practices for evaluating vapor cloud explosion (VCE) impacts to site occupied buildings. This reference introduces generic VCE frequencies for different types of process units that are based on VCE incidents database. Although these reported VCE frequencies are not capable of illustrating all parameters that affect explosion likelihood, they are widely used in risk analysis studies and software packages. This paper delineates the structure of a more realistic method for estimation of local VCE frequencies for independent congested spaces or units as a function of process, site, and meteorological variables. Compared to traditional methods for VCE frequency estimation, the new proposed approach is supported by an obviously more populated and precisely categorized database of leakage

frequencies and features a multi-variable functionality of process/plant conditions. Contrary to previous procedures that aimed at finding the frequency of occurrence for a single VCE incident, this proposed methodology characterizes each congested space with a local VCE frequency. This frequency is an integration of the frequencies pertaining to VCE's that are likely to be initiated by each congested space. This new VCE frequency can also be used to determine the level of explosion hazard in each unit and in risk matrix analysis.

- **Keywords:** Siting; Quantitative risk assessment; Vapor cloud explosion; Frequency; Building

Enrico Zio, Terje Aven. *Industrial disasters: Extreme events, extremely rare. Some reflections on the treatment of uncertainties in the assessment of the associated risks.* Pages 31–45.

This paper addresses the issue of risk from disasters occurring due to accidents in high-consequence technologies, e.g., nuclear and oil and gas. The focus is on the challenges posed to the representation and treatment of uncertainties in the assessment of such risk, given that the occurrence of such extreme disasters is extremely unlikely, and yet they occur. A general framework of analysis is proposed.

- **Keywords:** Industrial disasters; Rare events; Uncertainty; Risk; Probability; Interval probabilities; Dempster-Shafer theory; Possibility

Nima Khakzad, Faisal Khan, Paul Amyotte. *Dynamic safety analysis of process systems by mapping bow-tie into Bayesian network.* Pages 46–53.

Among the various techniques used for safety analysis of process systems, bow-tie (BT) analysis is becoming a popular technique as it represents an accident scenario from causes to effects. However, the BT application in the dynamic safety analysis is limited due to the static nature of its components, i.e. fault tree and event tree. It is therefore difficult in BT to take accident precursors into account to update the probability of events and the consequent risk. Also, BT is unable to represent conditional dependency. Event dependency is common among primary events and safety barriers. The current paper illustrates how Bayesian network (BN) helps to overcome these limitations. It has also been shown that BN can be used in dynamic safety analysis of a wide range of accident scenarios due to its flexible structure. This paper also introduces the application of probability adapting in dynamic safety analysis rather than probability updating. A case study from the U.S. Chemical Safety Board has been used to illustrate the application of both BT and BN techniques, with a comparison of the results from each technique.

- **Keywords:** Dynamic safety analysis; Bow-tie approach; Bayesian network; Probability adapting

Jing Wu, Laibin Zhang, Wei Liang, Jinqiu Hu. *A novel failure mode analysis model for gathering system based on Multilevel Flow Modeling and HAZOP.* Pages 54–60.

In complex industrial system, such as gathering system, the high complex failure coupling relation among separate production process sections, personnel operation and equipment leads to a high complex potential hazard, which induces huge economic losses, environmental contamination, or human injuries. In order to insure system intrinsic safety and simplify failure mode analysis, this study proposes a novel failure mode analysis model (NFMA).

NFMA is developed based on Multilevel Flow Modeling (MFM) and Hazard Operability Study (HAZOP). A graphical MFM model is introduced in NFMA by decomposing goals, functions and components, to describe flows of mass and energy of process system as basis of this model. According to the MFM reasoning rules, HAZOP investigates function nodes and deviations to identify the failure modes. Finally, the benefits and feasibility of NFMA are investigated with a case study of gathering system.

- **Keywords:** MFM; HAZOP; Gathering system; Failure mode analysis

Kamarizan Kidam, Markku Hurme. *Analysis of equipment failures as contributors to chemical process accidents. Pages 61–78.*

A database study of chemical process accident cases was carried out. The objective of the study is was to identify the reasons for equipment based accidents. The most frequent accident causing equipment were piping (25%), reactors and storage tanks (both 14%) and process vessels (10% of equipment accidents). The six most accident-prone equipment is process related involve nearly 80% of accidents.

78% of equipment accident contributors are technically oriented including design and human/technical interface faults. Purely human and organizational reasons are the most common accident contributors for storage tanks (33%), piping (18%) and heat transfer equipment (16% of causes). For other equipment the technical accident causes are most common.

The accident contributors were divided to main and sub-contributors. On average process equipment failures have 2.2 contributors. The contributors, which frequent and act often as main contributors, should be focused. These risky contributors were identified for several equipment types. Also a deeper analysis of the accident causes and their interconnections was made. Based on the analysis a checklist of main risk factors was created for hazard identification on different types of equipment.

- **Keywords:** Accident database study; Process equipment failures; Accident contributors; Hazard identification; Main risk factors

Xin-mei Zhang, Chen Chen. *Mechanism analysis and risk assessment of escalation scenario in chemical industry zones. Pages 79–85.*

Many major hazard installations (MHIs) are located in chemical industry zones and escalation effect may be triggered when the fire or explosion occurs on a MHI. To investigate the mechanism of the accident escalation, a systematic quantitative assessment methodology is proposed by the considering the feature and uncertainty of the escalation scenario. The main accident energy carriers of the escalation are heat radiation, overpressure of blast and fragments. The escalation probability, joint influence of the three energy carriers and risk characterization of the accident scenarios are carried out. By the new methodology, the escalation scenario in chemical industry zones can be analyzed and the risk escalation morphology is demonstrated by the simulation software. The visualized risk cloud figure gives a supplementary way to prevent the escalation scenario in chemical industry zones planning.

- **Keywords:** Escalation scenario; Risk characterization; Impact probability; Application

Qian Zhang, Shuwen Gong, Lijun Liu, Handong Yin. *An efficient and clean oxidative bromination reaction of phenol catalyzed by ammonium salt of heteropoly acids supported on silica. Pages 86–91.*

An efficient and eco-friendly oxidative bromination reaction of phenol has been achieved by treatment with $\text{KBr-H}_2\text{O}_2$ in the presence of a catalytic amount ammonium salt of molybdophosphoric acid or phosphotungstic acid that supported on silica, which were synthesized by sol-gel method. The physicochemical characterization indicated that supported catalysts still retained its Keggin type and the particles were well dispersed onto the surface of silica support. The evaluated results of liquid phase bromination of phenol showed that these catalysts exhibited high catalytic oxybromination activity and high *para* substituted selectivity, and good stability was also observed after recycling three times. Meanwhile, no highly toxic and corrosive materials were used and formed in the reaction process, which makes this process environmentally benign. The influences of the reaction time, catalyst amount and solvent on oxidative bromination reaction were also investigated.

- **Keywords:** Ammonium tungstophosphat; Catalysis; Phenol; Oxidative bromination

I. Waddington, W.J.O. Boyle, J. Kearns. *Computing the limits of risk aversion. Pages 92–100.*

Utility theory can be used to model the decision process involved in evaluating the cost-effectiveness of systems that protect against a risk to assets. A key variable in the model is the coefficient of relative risk aversion (or simply "risk-aversion") which reflects the decision maker's reluctance to invest in such safety systems. This reluctance to invest is the scaled difference in expected utility before and after installing the safety system and has a minimum at some given value of risk-aversion known as the "permission point", and it has been argued that decisions to sanction safety systems would be made at this point. As the cost of implementing a safety system increases, this difference in utility will diminish. At some point, the "point of indiscriminate decision", the decision maker will not be able to discern any benefit from installing the safety system. This point is used to calculate the maximum reasonable cost of a proposed safety system. The value of the utility difference at which the decision maker is unable to discern any difference is called the "discrimination limit".

By considering the full range of accident probabilities, costs of the safety system and potential loss of assets, an average risk-aversion can be calculated from the model. This paper presents the numerical and computational techniques employed in performing these calculations. Two independent approaches to the calculations have been taken, the first of which is the derivative-based secant method, an extension of the referred derivative method employed in previous papers. The second is the Golden Bisection Method, based on a Golden Section Search algorithm, which was found to be more robust but less efficient than the secant method. The average risk-aversion is a function of several key parameters: the organisation's assets, the probability and maximum cost of an incident, and the discrimination limit. An analysis of the sensitivity of the results to changes in these parameters is presented. An average risk-aversion of 0.8–1.0 is found for a wide range of parameters appropriate to individuals or small companies, while an average risk-aversion of 0.1 is found for large corporations. This reproduces the view that large corporations will be risk neutral until faced with risks that pose a threat to their viability.

- **Keywords:** Risk aversion; ABCD model; Reluctance to invest; Point of indiscriminate decision; Risk multiplier

B.J. Lowesmith, G. Hankinson. *Large scale experiments to study fires following the rupture of high pressure pipelines conveying natural gas and natural gas/hydrogen mixtures. Pages 101–111.*

As part of the EC funded Naturalhy project, two large scale experiments were conducted to study the hazard presented by the rupture of high pressure transmission pipelines conveying natural gas or a natural gas/hydrogen mixture containing approximately 22% hydrogen by volume. The experiments involved complete rupture of a 150 mm diameter pipeline pressurised to nominally 70 bar. The released gas was ignited and formed a fireball which rose upwards and then burned out. It was followed by a jet fire which continued to increase in length, reaching a maximum of about 100 m before steadily declining as the pipeline depressurised. During the experiments, the flame length and the incident radiation field produced around the fire were measured. Measurements of the overpressure due to pipeline rupture and gas ignition were also recorded. The results showed that the addition of the hydrogen to the natural gas made little difference to radiative characteristics of the fires. However, the fraction of heat radiated by these pipeline fires was significantly higher than that observed for above ground high pressure jet fires (also conducted as part of the Naturalhy project) which achieved flame lengths up to 50 m. Due to the lower density, the natural gas/hydrogen mixture depressurised more quickly and also had a slightly reduced power. Hence, the pipeline conveying the natural gas/hydrogen mixture resulted in a slightly lower hazard in terms of thermal dose compared to the natural gas pipeline, when operating at the same pressure.

- **Keywords:** Large scale experiments; Natural gas/hydrogen mixtures; Transmission pipeline fires

G. Gallastegui, A. Barona, N. Rojo, L. Gurtubay, A. Elías. *Comparative response of two organic biofilters treating ethylbenzene and toluene after prolonged exposure.* Pages 112–122.

The response of two biofilters filled with an organic waste material for treating ethylbenzene and toluene was studied for 415 and 472 operating days, respectively. The peak elimination capacities (EC_{MAX}) recorded were $170 \text{ g m}^{-3} \text{ h}^{-1}$ for ethylbenzene (EC_{MAX}) and $138 \text{ g m}^{-3} \text{ h}^{-1}$ for toluene. Regarding the degradation profile through the biofilters, an increase in the inlet concentration displaced the degradation profile into the downstream section. A sudden decrease in the performance of both biofilters occurred when the moisture content (MC) of the packing material exceeded 37% for ethylbenzene and 30% for toluene. Thus, a recommended MC value was established in the 15–30% range. Given the bioreactor was operated at a low MC level, fungi prevailed over bacteria. Nevertheless, synergism was detected between both microorganism types for the mineralization of the aromatic hydrocarbons.

- **Keywords:** Biofiltration; Toluene; Ethylbenzene; Organic packing material; Biodegradation

Khim Hoong Chu, Xiao Feng. *Enzymatic conversion of newspaper and office paper to fermentable sugars.* Pages 123-130.

Two types of waste paper materials, newspaper and office paper, were evaluated for their potential to be used as renewable feedstock for the production of fermentable sugars via the enzymatic hydrolysis of their cellulose fractions. The effects of four factors (hydrolysis time, enzyme loading, surfactant addition and phosphoric acid pretreatment) on the extent of sugar yield were assessed and quantified by using a methodical approach based on response surface methodology. The statistical experimental design used in this study requires fewer experimental runs compared to some commonly used experimental designs. In the newspaper hydrolysis case, response surface plots revealed that the degree of sugar release increased with an increase in hydrolysis time but it was hardly affected by the enzyme loading and acid pretreatment factors. The surfactant addition factor exhibited a positive effect when the enzyme loading level was relatively low. With office paper as the substrate, three of the four factors (hydrolysis time, enzyme loading and acid pretreatment) exhibited positive effects on the extent of sugar

release. At local optimum conditions, the maximum sugar yield from office paper was found to be 0.82 g of reducing sugars per gram of paper, which was about 4.8 times higher than the maximum sugar release from the newspaper substrate.

- **Keywords:** Hydrolysis; Lignocellulosic; Optimization; Response surface; Waste paper

Aminul Islam, Yun Hin Taufiq-Yap, Chi-Ming Chu, Eng-Seng Chan, Pogaku Ravindra. *Studies on design of heterogeneous catalysts for biodiesel production.* Pages 131-144.

The production of biodiesel is gaining momentum with the ever increasing demand of the fuel. Presently, limited literature is available with respect to well designed solid heterogeneous catalyst for biodiesel production considering all the characteristics, process and operation parameters. Hence, a study was conducted to design effective heterogeneous catalyst for biodiesel production. Further, the significant impact of different catalysts, different feed stock, various reaction conditions such as temperature, methanol oil molar ratio, catalyst concentrations and stability/inactivation of the catalysts, are detailed out for transesterification process of biodiesel production. Based on the studies it can be concluded that well designed heterogeneous catalyst can yield high throughput of biodiesel.

- **Keywords:** Biodiesel; Transesterification; Heterogeneous catalyst; Feed stock

Chunjing Liu, Jia Liu, Jian Li, Hong He, Shujing Peng, Chao Li, Ying Chen. *Removal of H₂S by co-immobilized bacteria and fungi biocatalysts in a bio-trickling filter.* Pages 145-152.

Biological control of odor gases has gained more attention in recent years. In this study, removal performance of a vertical bio-trickling filter inoculated with bacteria and fungi was studied. Bacteria and fungi were isolated from activated sludge in a sewage treatment plant. By adopting "three step immobilization method", the bio-trickling filter could degrade pollutant immediately once hydrogen sulfide (H₂S) passed. The optimal empty bed resident time was 20 s. The optimal elimination capacity was about 60 g H₂S m⁻³ h⁻¹ with removal efficiency of 95%. And the maximum elimination capacity was 170 g H₂S m⁻³ h⁻¹. Pressure drop was ranged between 5 and 15 mm H₂O per bed over the whole operation. Removal efficiency was not affected obviously after terminating nutrient supply. The bio-trickling filter could recover back after shut down H₂S gaseous and liquid supplies simultaneously. Microbial community structure in the bio-trickling filter was not changed significantly.

Combining bacteria and fungi would be a better choice for inoculation into a bio-trickling filter because of the quickly degradation of H₂S and rapid recovery under shut-down experiment. This is the first study attempting to combine bacteria and fungi for removal of H₂S in a bio-trickling filter.

- **Keywords:** H₂S; Bacteria; Fungi; Co-immobilization; Bio-trickling filter

Sang Joon Chung, Il Shik Moon. *An improved method of removal for high concentrations of NO by electro-scrubbing process.* Pages 153-158.

In the Ag(II)/Ag(I) redox mediator integrated scrubber system, NO reacts with the Ag(II) ions produced by the electrochemical oxidation of Ag(I) in an electrochemical cell present in the scrubbing solution (aqueous HNO₃ acid) to form NO₂. This NO₂ is then absorbed into the scrubbing solution and degraded to nitrate. Numerous experimental runs were carried out to evaluate the feasibility of the integrated system to treat industrial waste

gases containing high NO_x levels. The results showed that the levels of NO and NO_x removal increased with increasing Ag(II) loading and contact time. Under optimized conditions, 93.5% and 73.3% of the NO and NO_x, respectively, were removed by a single stage gas scrubber with 1.62 g L⁻¹ Ag(II) operating at 25 °C and atmospheric pressure.

- **Keywords:** NO; NO_x; Wet scrubber; Mediated electrochemical oxidation; Ag(I)/Ag(II) redox system