

APPLICATION OF RISK REDUCTION STRATEGIES IN THE CHEMICAL PROCESS INDUSTRY

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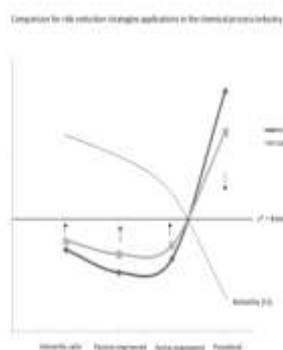
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Graphical abstract



Abstract

Recent accident analyses show that the accident rates in the chemical process industry (CPI) were still not decreasing. In the paper, the issues and challenges of risk reduction strategies were discussed. A case study using accident cases, extracted from the U.S. Chemical Safety and Hazard Investigation Board (CSB) database was conducted. The results of the accident analysis were discussed and then compared to previous analysis of the Failure Knowledge Database (FKD, Japan). The CSB analysis shows that the industry had moved from procedural risk reduction strategies to inherently safer and add-on engineered strategies. After 10 years improvement, the industry was approaching towards more balanced safety management to prevent occurrence and recurrence of accidents with the emphasis on both management and engineering risk reduction strategies.

Keywords: Accident contributor, risk reduction strategies, hierarchy of controls.

Abstrak

Analisa terkini kemalangan dalam industri pemprosesan kimia tidak menunjukkan sebarang pengurangan dalam kadar kemalangan di tempat kerja disebabkan kekangan dalam pelaksanaan langkah-langkah kawalan risiko untuk mengelakkan kemalangan. Kajian kes juga dijalankan dengan menggunakan data dari pusat data CSB. Dapatan kajian kes tersebut dibandingkan dengan analisa data dari pusat data FKD. Berdasarkan perbandingan yang dibuat, pihak industri telah mula beralih dari kawalan risiko bersifat prosedur kepada pencegahan awal melalui kejuruteraan rekabentuk. Selepas 10 tahun, pihak industri kini telah mewujudkan kawalan risiko kemalangan yang seimbang untuk mencegah kemalangan dan kemalangan berulang.

Kata kunci: Kemalangan, punca kemalangan, kawalan risiko, hierarki kawalan.

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1.0 INTRODUCTION

The rapid industrialization in the 1960s to 1990s triggers the advancement of chemical plant technologies and develops plentiful safety knowledge within the chemical process industry (CPI). Although many risk reduction strategies have been introduced, the accident rates of the CPI are still not decreasing.^{1,2} According to Pasman, in the 1960s, the focuses of the risk reduction strategies was more on technical aspects and are design-oriented. Later, on the 1980s the risk reduction strategies focused on human and management-centered with active add-on controls.³

As time passes, the focus of current risk reduction strategies has changed. Most of the time, these strategies utilize the outer layers of protection by adding add-on engineered controls either passive or active; and procedural control strategies. Often, the most inner layer of protection i.e. the inherent safer layer is ignored.⁴ Nowadays, the risk reduction strategies applied are frequently related to human and organizational factors, emphasizing on the safety management system and safety culture. However, the accident rates of the industry remain persistently high.⁵ These available risk reduction strategies are only effective to a certain extent, leading to non-decreasing accident rates in the CPI. This paper discusses the issues and challenges of these risk reduction strategies for accident prevention and reduce the accident rates of the CPI.

2.0 HIERARCHY OF CONTROLS FOR RISK REDUCTION STRATEGIES

Most of the accidents in the CPI often recurred and these accidents could be avoided using the existing knowledge but unfortunately the industry never learns from it. It is reported that accidents with similar causes are recurring within a five-year interval.⁶ Common identified characteristics of major accidents in the CPI of the last decade are; (1) their occurrence was not due to unknown physical/chemical process hazards, (2) none of the accidents happened due to a single problem/failure but with multiple flaws, lacks and deficiencies, (3) accident contributors is mainly related to management/organization quality and human factors, and (4) complexity of the process installations.⁷ Therefore, many risk reduction approaches have been developed as the level of knowledge on technical, design, operational and management of the CPI evolves.

Risk reduction strategies are used to eliminate hazards and reduce risks in the CPI. Risk reduction strategies in the chemical process industry could be divided into four major categories; (a) risk reduction in materials, (b) risk reduction in design, (c) risk reduction in operation, and (d) risk reduction in maintenance.⁸ Risk is reduced in materials by selecting a good quality and compatible material. Risk reduction in design can

be applied during process engineering and detailed engineering stages. To reduce risk in design, the basic control strategy should be established and all conditions such as start-up, normal operation and emergency shut-downs have to be considered. Risk reduction in operation comprises of safety and environmental management systems, controls of the safety management system, accident and investigation, and operating procedures. Meanwhile, risk reduction in maintenance deals with permits to work, maintenance programs, and modification controls. In these categories, human resources and management are required to eliminate human errors by giving education and training, and improving communications among the personnel in the CPI.⁹

Hierarchy of risk reduction strategies consists of four layers of protection, listed in decreasing order of reliability: inherently safer, passive add-on engineered active add-on engineered, and procedural. The inner most layer is inherent safer and the outer most layer is procedural strategies. Three main functions of the hierarchy of control are prevention, protection, and mitigation. Prevention is the primary containment of chemicals or energy during storage, transfer, and process to reduce the probability of accidental releases using process design, basic controls, and critical alarms and operation action. When the primary measures failed, protection systems such as Safety Instrumented System (SIS), physical relief devices, and passive physical protection systems response to the release. Protection detects, contains, and neutralizes the release before escaping into the environment. A protection system failure triggers the mitigation function of the layers of protection that limits and mitigates on and off-site severity of the consequences of a release. Among mitigation systems available are active protection systems, plant emergency response, and community emergency response.¹⁰

2.1 Inherently Safer

Based on CCPS, inherently safer is the premier strategy for hazard avoidance and control at its source through design changes. By inherent safety principles, elimination is used to avoid hazard by design; intensification, substitution or attenuation is used to reduce the severity of the hazard; and simplification of process or plant is used to reduce the likelihood of the hazard occurring.¹¹ Using moderation principle, the existing processing condition is changed to less severe condition by manipulating temperatures, pressures, concentrations and physical states of the chemicals.¹² Substitution is done by selecting safer and compatible chemicals. Use of safer chemical reduces the severity of accident.¹³

A process plant can be simplified using credible equipment and establishment of a reliable or self-regulating system. The system reduces the need for redundant systems and complicated controls.

Thus, a simpler and more robust design is the key for reliable and safer chemical plant operations.¹⁴ Meanwhile, error tolerance is effectively being used as an inherently safer strategy to solve problems related to wrong material selection; corrosion; chemical reactivity; incompatibility; and sub-standard equipment application. Majority of the corresponding corrective actions amend the existing technical and design deficiencies that led to process failure. The idea is to redesign the default part of the plant (or equipment) to a robust and accident-resistant design.¹⁵

2.2 Passive-Engineered

Add-on layers are mainly installed as passive and active engineered safety protection systems. Passive strategy employs systems that remain static and do not perform any fundamental operations. This passive-engineered risk control further reduces the likelihood and consequences of an accident by using passive safety protection such as dikes, containment and fire wall.¹¹ The passive-engineered modifications are mostly related to layout, mechanical/physical aspects, design specification changes, additional equipment, equipment modification, and friendlier design.

The common errors in plant layout are the incorrect arrangement and safety distance between main processing equipment which eventually increase the severity of damage due to domino effect. The detailed layout changes for safety distance normally involve redesigning and repositioning of piping system; and reshaping of specific equipment or parts. Other safety issues related to plant layout are equipment accessibility and visual obstacles are improved using proper organization of plant layout. The mechanical and passive engineering control changes material of construction for a better robust; and corrosion-and-high-pressure-resistant process equipment. The design specification is applied to equipment with changes in process condition, fire and explosion ratings. Additionally, plant and equipment modifications are carried out in order to improve human-machine interface leading to user-friendlier process which reduces the occurrence and recurrence of human-related errors.¹⁵

2.3 Active-Engineered

Active add-on engineered strategies use active systems that depend on timely hazard detection and initiation (i.e. utilizes safety devices that respond to process changes) to further reduce the accidents

using relief valves, controllers, detectors and alarms. For controlling risk, active-engineered control requires additional devices to sense and indicate process variables, valves, etc. either by adding or removing the instrumentation and automation of the equipment.¹¹ Among the common active-engineered control strategies are: modifying control setting specification; supplementing additional instrumentation; and introducing new protection systems. To specify control setting, majority of actions are conducted to accurately set the safety limits for flow rate, temperature, pressure, density and speed of the automation system.¹⁵

Past analysis found out that the correct number of control instrumentations is important for early detection of process deviation. A number of temperature and pressure-related accidents have been reported due to lack of sensors or detectors e.g. chemical reactors require adequate number of detectors with correct positioning. In addition, the process equipment needs relief and mitigation systems to avoid such as Seveso and Bhopal.¹⁶ The accidents had severe consequences as a result of under-designed protection and mitigation systems. Thus, suitable protection and mitigation systems based on the worst-case scenario with adequate design capacity are essential to manage process hazards and reduce risks.

2.4 Procedural

Procedural or human and organizational-oriented risk control usually focuses on safe operation including training, supervision, procedure, work instructions, inspection and maintenance. This operator and maintenance procedures should be the last resort, especially for control and mitigation where the chance of errors or failure is high.¹¹ Among the highest procedural corrective actions were proper documentation; improved management system; continuous monitoring/supervision; and training.

The gathered data indicates that poor organizational support of work system and ineffective management systems have potential to cause accidents. Confusion might arise from poor or unclear documentation and increases chances of operators to perform incorrect work sequences and taking shortcuts. To deal with these attitudes, effective safety management system and safety culture education are essential in promoting safety awareness among the CPI players.¹⁷ Table 1 summarizes these four categories of LOP for potential process safety systems design.

Table 1 Summary of potential process safety systems design solution [11]

Details	Inherently Safer	Passive-engineered	Active-engineered	Procedural
Design Solution	Use materials and process conditions that are less hazardous to eliminate and mitigate hazard	Do not require any device to sense and/or actively respond to a process variable and have a very reliable mechanical design	Require devices to monitor a process variable and function to mitigate a hazard.	Require a personnel to perform an action to avoid a hazard i.e. administrative controls
Examples	<p>Minimize/Intensification: Use smaller quantities of hazardous substances</p> <p>Substitute: Replace a material with a less hazardous substance</p> <p>Moderate/Attenuation/Limitation of Effects: Use less hazardous conditions and form of material</p> <p>Simplify/Error Tolerance: Eliminate unnecessary complexity and make operating errors less likely</p>	<p>Use incompatible hose couplings, non-flash filling, permanent grounding and bonding via continuous metal equipment and pipe.</p> <p>Design high pressure equipment to contain overpressure hazards such as internal deflagration</p> <p>Contain hazardous inventories with a bottom- sloped dike to minimize surface area.</p>	<p>Use a pressure safety valve or rupture disk to prevent vessel overpressure.</p> <p>Interlock a high level sensing device to a vessel inlet valve and pump motor to prevent liquid overflow of the vessel Install check valves</p>	<p>Follow standard operating procedures to ensure process operations within established equipment mechanical design limits</p> <p>Manually close a feed isolation valve in response to a high level alarm to avoid tank overfilling</p> <p>Implement preventive maintenance procedures to prevent equipment failures</p> <p>Manually attach bonding and grounding systems</p>
Layer				Outer most layer
Reliability				Less reliable

3.0 CASE STUDY

Most accident investigation studies analyzed the efficiency of previous decade's technology before any technical escalation. Therefore, additional analysis on current database is required to evaluate the effectiveness of current accident data to propose another improvement for future technology. All the data could be used in assessing the gaps in current risk reduction strategies and prevent accidents from occurring or recurring in the industry. In the research, 75 accident cases from U.S. Chemical Safety and Hazard Investigation Board (CSB) databases were analyzed.¹⁸ This database was established in 1998. The investigations are more reliable since CSB itself involved in accident investigation instead of only receiving reports from others. The database is fresh-updated and related to CPI accident cases. However, accident cases from 2012 onwards are not included because the accidents are still under investigation.

Figure 1 shows the frequencies of CPI accidents (1995-2011), extracted from the database. CPI has been known with its highly hazardous environment compared to other industries. Many accidents happen in the CPI due to the existence of

reactive/toxic chemicals and state-of-the-art technologies. The accidents commonly risk life and damage physical assets and its surrounding. From the analysis, 44% of the accidents led to explosion, 36% led to fire, and 19% led to toxic release. Only 1% led to chemical spills. As the consequences of the major hazards, 155 fatalities, 774 injuries, and 221 exposures were reported. The accidents also led to on-site and off-site evacuations i.e. 59 and 16 evacuations, respectively.

The highest number of accidents occurred in 2003. No major accidents involving death, major losses and major evacuation occurred in 1996 and 2000 were investigated by the CSB. Hence, there were no accident cases reported in 1996 and 2000. From the graph, the accident rate increased from 1995 to 2003 but slowly decreasing onwards. Initially, accident rate increased as the industry faced extreme operating conditions to cope with the high production demands, existence of reactive/toxic chemicals inventories, and introduction of new state-of-the-art technologies. As time passed, the industry was capable to deal with these issues by incorporating safety knowledge, training, and technical improvement throughout process plant lifecycle thus leading to a decrease in accident rate.

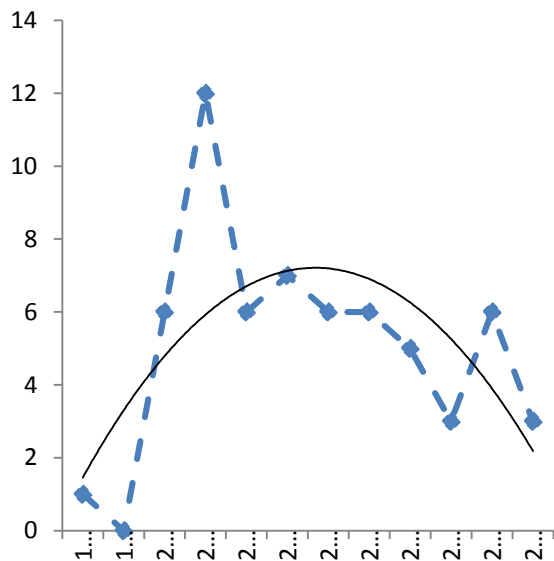


Figure 1 Accident occurrence trend for CSB database analysis

3.1 Accident Contributors Analysis

In the study, the accident contributors were grouped into four major types; organizational faults, design, technical errors, human errors, and nature. Based on the analysis, organizational errors were the highest accident contributors (29%), followed by design and technical errors, 26% and 23% respectively. Human errors contributed to 20% of the reported accidents. Nature is any physical and natural events such as bad weather, earthquake, floods, lightning, landslides, and some other random effects. Nature played the least role in leading to the accident with only 2% contributions (Table 2).

Table 2 Accident contributors for the CSB database analysis

Type of Accident Contributors	Percentage
Organizational errors	29%
Design errors	26%
Technical errors	23%
Human errors	20%
Nature	2%

Most of the organizational errors (29%) were due to lacks of safety culture and major accident prevention programs; insufficient maintenance and housekeeping; lacks of inspections and auditing programs; inadequate emergency preparedness; and management of change. Among organizational errors identified were no formal written program in place to identify, review, and freeze-protect dead-legs or frequently used piping and equipment; top management did not provide effective oversight of the company's safety culture and major accident prevention programs; had an ineffective hazard

communication program; did not perform a management of change review to ensure proper design of equipment; and no formal, documented program to investigate and implement corrective actions for incidents resulting in fires, explosions or toxic releases.

Although design errors are parts of technical errors but due to their significant impacts on accidents, design errors were classified into their own grouping. Design error is deemed to have occurred if the design or operating procedures are changed after an occurrence of an accident.¹⁷ Design errors involved inappropriate process condition selection, lack of hazard analysis, unsuitable equipment, components or parts, wrong specification of material for construction, inappropriate sizing, inadequate layers of protection, improper layout or equipment siting, inadequate automation and instrumentation, wrong operating procedures, and other fabrication/construction/installation issues such as welding defects and insufficient installation of engineering control at the facility to prevent explosions.

Contamination, heat transfer, reaction, corrosion, vibration, erosion, flow and utilities-related fabrication, construction and installation, and mechanical failures errors were classified as technical errors. In the analysis, technical errors identified were mostly related to reaction, fabrication, construction, and installation, and mechanical integrity. Among reaction errors were runaway reactions and unwanted chemical reaction due to chemical reactivity and incompatibilities. Fabrication, construction, and installation errors were faults in design specification, quality of work, welding, reconditioning, and reusing items for other applications. Mechanical integrity was often related to automation and instrumentation such as failures of alarms and level indicators, and malfunctioning of equipment.

Human errors are classified into four major categories: (1) errors due to slip or momentary lapse, (2) errors due to poor training or instructions, (3) errors due to mismatch between the ability of the person and the requirement of the task, and (4) errors due to a deliberate decision not to follow instructions or accepted practices as people often believe that the rule is wrong or the circumstances justify an exception. Examples of human errors identified were inadequate training and experience on procedural safeguard, did not formally train the junior technician, and the maintenance supervisor did not fully understand the hazards associated with the process.

3.2 Recommended Risk Reduction Strategies

Risk reduction can be managed using Management Preventive Action (MPA) and Engineering Preventive Action (EPA). Generally, the CPI is engineering-maintained using inherently safer process design which reduces the safety risk and add-on devices for the explicit purpose of reducing risk or mitigating of

upsets.¹⁰ Inherent safety is related to the intrinsic properties of the process design such as the use of safer chemicals and operating conditions.¹⁹ According to CCPS, Process Safety Management (PSM) which is the commonly applied MPA consists of twenty elements and can be grouped into four major categories: (1) commit to process safety i.e. process safety culture, compliance to standards, process safety competency, workforce involvement, and stakeholder outreach; (2) understand hazards and risk i.e. process knowledge management, and hazard identification and risk analysis; (3) manage risk i.e. operating procedures, safe work practices, asset integrity and reliability, contractor management, training and performance, management of change, operational readiness, conduct of operations, and emergency management; and (4) learn from experience i.e. incident investigation, measurement and metrics, auditing, and management review and continuous improvement.²⁰

Ideally, accident preventive approach framework recommends inherently safer approach to deal with design errors and nature. For human and organizational causes, procedural approach is usually applied. Add-on engineering controls (i.e. passive and active-engineered) are recommended for technical-related accidents. Most CPI prefers to apply MPA than EPA although nature, design and technical errors play significant roles as accident contributors. The implementation of EPA as risk reduction strategies should be encouraged in the industry for more balance accident prevention. Moreover, EPA is more reliable than MPA. ¹¹Based on the analysis, 44% of the recommendations are MPA; others are EPA, 56% (Table 3). Inherently safer strategies applied as corrective actions were 20%. For add-on engineering controls, passive-engineered strategies constituted to 17% of the corrective actions meanwhile active-engineered strategies were 19%.

As expected, procedural strategies were the most applied risk reduction approach for CSB database i.e. 44%. As mentioned previously, EPA strategies are often used to prevent accidents due to nature, technical and design errors. In the research, about 51% of accident contributors were nature, technical and design-oriented errors. MPA strategies are the best approach in dealing with human and organizational errors. About 49% of accident contributors were human and organizational-related and were corrected using 44% procedural or MPA strategies.

Table 3 Risk reduction strategies for the CSB analysis

Risk Reduction Strategies	Percentage
Management Preventive Action (MPA)	44%
Engineering Preventive Action (EPA)	56%

Inherently safer approach commonly involved minimization, simplification, substitution, moderation,

error tolerance, and limit of effect strategies. Simplification of the piping system and unit operation, use of mechanically stronger or robust components, changing to safer process condition and simpler process plant, substitution of chemicals or operating procedures, proper selection of protective system to limit the consequence of incidents, and solving problem related to wrong material selection were among available inherently safer corrective approaches recommended by the board to improve the plant safety.

Add-on engineering strategies such as passive-engineered and active-engineered strategies were less adopted in the recommended corrective actions. Passive-engineered risk reduction strategies do not require any device to actively respond to a process variable but the approaches involved alteration in design, layout, process condition, protective system, sizing, material specification, and robust equipment/system. Sufficient security measures were suggested by the board to prevent accident such as a full fence surrounding storage tanks with locked gate, hatch locks on tank manways, and barrier securely attached to tank external ladders or stairways.

Active-engineered strategies need additional devices to monitor a process variable and function to mitigate a hazard. Commonly used active-engineered strategies applied add-on mitigation system, equipment modification, design specification, automation, and instrumentation. The board required facilities that handle toxic and highly toxic materials in compressed gas cylinder to include enclosures, ventilation and treatment systems, interlocked fail-safe shutdown valves, gas detection and alarm systems, and similarly relevant layers of protection to further reduce the likelihood and consequences of accidents in the industry.

Procedural strategies applied for corrective actions for the analysis can be grouped to maintenance, inspection, monitoring/supervision, management system, documentation, management system, emergency preparedness, communication, cleaning, and contractor control. The most common procedural strategies were related to management system. For example, the board suggested for policy guidance development to provide a regulatory process with rigorous safety review, new or revised agreements recommendations, and roles and responsibilities establishments for ownership, management, execution and resolution of recommendations from incident or near-miss investigation at the facility.

3.3 Discussion

As the complexity and technologies of the industry advance, the high production and extreme operating conditions may lead to disasters. These accidents would not only damage the industry in term of the financial losses but also in terms of societal losses,

irreversible environmental damage and major regulatory restrictions.² Most accident analyses provide very case specific information and is generally difficult to apply. Therefore, new findings on general knowledge and understanding of risk reduction strategies are still greatly lacking, especially on plant design. Today, employing accident databases for accident analysis is becoming an active agenda. However, little effort has been made to utilize the information to improve the risk reduction strategies due to poor accident investigation, analysis and reporting.^{2, 21}

Application of hierarchy of controls in reducing hazards and controlling risks using the inner most layer of protection (i.e. inherently safer) is more reliable than using add-on engineered or procedural approaches.¹¹ Regardless of the less reliability of these outer layers of protection, the industry still emphasizes on using passive-engineered, active-engineered and procedural strategies. In most cases, the industry is more to cheaper procedural strategies.^{21, 22}

According to Amyotte et al., 42% of the recommended corrective actions for 63 reports, studies, and bulletins issued by the U.S. Chemical Safety and Hazard Investigation Board (CSB) extracted from CSB database were procedural-based or MPA. Inherently safer and active-engineered were 36% and 14%, respectively. The least recommended action was passive-engineered (8%).²³Based on another study by Kidam et al. on 364 accidents extracted from Japan Failure Knowledge Database (FKD) from 1964 to 2003, the corrective actions taken by the CPI were reported to be almost equally shared between MPA and EPA, 53% and 47% respectively.

For EPA, inherently safer approach was the highest i.e. almost 18% of all the implemented corrective actions. The active and passive-engineered were 16% and 13%, respectively. The outer most layer of hierarchy of control was the most commonly applied strategies with 53% of the corrective actions were procedural strategies (Table 4).¹⁵Although both studies showed an equal distributions of engineering and management preventive actions, but further classifications of the accident preventive actions indicated unbalanced applications of inherently safer, passive-engineered, and active-engineered strategies.

Table 4 Comparison for current risk reduction strategies

Risk Reduction Strategies	Amyotte et al. [38]	Kidam et al. [39]
Management Preventive Action (MPA)	42%	53%
Engineering Preventive Action (EPA)	58%	47%

Higher hierarchy of control such as inherently safer and passive-engineered strategies should be prioritized by encouraging hazard elimination and risk reduction at the early phase of plant design. Prevention through design (PtD) reduces the risk of injury, illness and environmental damage by integrating hazard analysis and risk assessment methods early in the design and engineering stages.²⁴

By applying PtD, productivity can be improved, operating cost decreases, risk reduction becomes more significant, and expensive retrofitting can be avoided.²⁵ Thus, PtD should be the main agenda in today's loss prevention approach. This is critical based on several studies which claimed that the technical and design-related contributions to accidents were significant.^{3, 25, 26} Furthermore, more balanced approach in risk reduction is essential for safe design and operation of the process plant.

The most current study by Kidam et al. represented past situations of the industry with a mean year of 1990.¹⁵ On the other hand, this research represents conditions of the industry for the past ten years with a mean year of 2003 (Table 5). In between the year gaps, several improvements were made in the industry as investigations and research led to an increase in the development of safety tools, techniques, method, and systems.²⁷

Although the industry gained major achievements in cultivating safety culture throughout the organization but accident rates were still not decreasing due to saturation of safety knowledge with the best safety practices had been applied. Nevertheless, the root causes of most organizational and human errors were inherited from poor design of process condition, equipment, or plant. From procedural or management risk reduction strategies emphasis, the industry moved to inherently safer and add-on engineered approaches to cope with these issues.

Thus, in comparison to FKD previous study, the industry was approaching toward more balanced safety management to prevent occurrence and recurrence of accidents as indicated by Table 5 and Figure 2.

Table 5 Comparison of hierarchy of controls

Hierarchy of Control	Kidam et al. [39] Mean = 1990	This paper Mean = 2003	Average
Inherently Safer	18%	20%	19%
Passive-engineered	13%	17%	15%
Active-engineered	16%	19%	17.5%
Procedural	53%	44%	48.5%

In Figure 2, y^* indicates the balance implementation target for risk reduction strategies of the industry. In order to attain the target, EPA should be increased and MPA should be decreased. To balance the risk reduction application, the industry should be advised on the commonly adapted management-related strategies which are less reliable compared to EPA. Among all the EPA, inherently safer is the best solution for almost all types of errors by eliminating hazards and reducing risks at the source.

Process safety of the CPI will be improved by application of inherently safer technology on new and existing plant layout design. Development of inherently safer technology database and libraries as well as inherently safer tools is a must for disseminations of the accident prevention knowledge throughout process safety management and chemical engineering community.

4.0 CONCLUSION

Based on the CSB analysis, 49% of the identified accident contributors were technical and design-oriented. The CSB had recommended 56% EPA and 44% MPA as the corrective actions. This new trend shows that the CPI are moving from outer layer of LOP to inner layer of LOP which is more reliable in preventing similar accidents. However, the recommended accident preventive actions were still unbalanced since only 20% of the recommended corrective actions were inherently safer strategies. In summary, the uptake of inherently safer design (ISD) and technology are still slow, resulting in high probability of accident reoccurrences due to less reliable corrective action applied by the CPI. Thus, in order to balance the applied risk reduction strategies, the implementation of ISD should be encouraged.

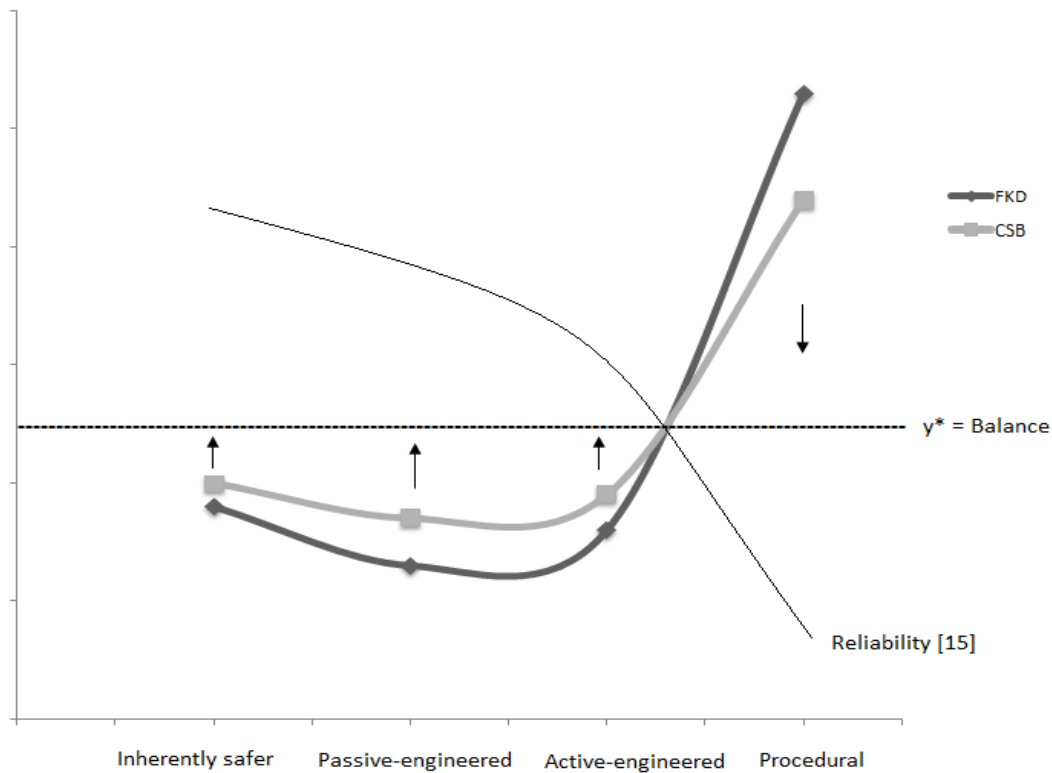


Figure 2 Comparison for risk reduction applications based on hierarchy of controls

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